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EVALUATION OF FLAME ARRESTOR MATERIALS FOR AIRCRAFT FUEL SYSTEMS (U)

Ralph J. Cato
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Joseph M. Kuchta

BUREAU OF MINES

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FOREWORD

This report was prepared by the Explosives Research Center of the U. S. Bureau of Mines under USAF Contract No. DO 33(615)-66-5005. The contract was initiated under Project No. 3048/6075 "Fire and Explosion Hazard Assessment and Prevention Techniques for Aircraft." It was administered under the direction of the Air Force Aero Propulsion Laboratory, Research and Technology Division, with Mr. Benito P. Botteri acting as project engineer. The assistance provided by Mr. L. Mahood, SEG(SEJIF) in the pursuit of this program is also appreciated.

This report is a summary of the classified work recently completed under this contract during the period 1 January 1966 to 31 December 1966. This report is classified because it contains information on advanced passive defense techniques for aircraft systems. The unclassified work under this contract is being reported on in another separate report. This report was submitted by the authors February 13, 1967.

Dr. Robert W. Van Dolah was the administrator for the U. S. Bureau of Mines and Messrs. Joseph M. Kuchta, Ralph J. Cato, Aldo L. Furno, Alphonse Bartkowiak, and Whittner H. Gilbert actively participated in this work at the U. S. Bureau of Mines Explosives Research Center, Bruceton, Pennsylvania.

This technical report has been reviewed and is approved; it contains no classified information extracted from other classified documents.

Arthur V. Churchill

ARTHUR V. CHURCHILL, Chief
Fuels, Lubrication and Hazards Branch
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SECRET ABSTRACT

Experimental data are presented from small-scale and full-scale experiments on the flame arrestor effectiveness of a polyurethane foam material with 10 pores/inch. Tests were conducted which verified the effectiveness of the 10-pore/inch material for use in at least a fully-packed aircraft fuel tank configuration at atmospheric pressure conditions. In addition, various flame arrestor void configurations designed for external and integral fuel tank applications were examined with near-stoichiometric n-pentane or n-butane and air mixtures at various pressures (0 to 20 psig) and ambient temperature conditions. In the small-scale experiments conducted with cylindrical arrestor segments, the effectiveness of the candidate arrestor material was influenced by variations in the diameter of the test vessel, arrestor length (ℓ_2), flame run-up distance or ignition void length (ℓ_1), initial combustible mixture pressure, and fuel vapor-air ratio. Observed pressure rises at a mixture pressure of 0 psig were generally less than 10 psi at ℓ_2/ℓ_1 ratios greater than about 1.5; they increased greatly at ratios less than this value. Also, fuel-wetted arrestors were much more effective in preventing flame propagation than dry ones. Results from three full-scale experiments at 0 psig initial pressure in a 450-gallon aircraft fuel tank indicated that the pressure rises developed are relatively small (< 10 psi) when the tank is packed to about 50 volume percent or more with the dry arrestor material; the flame arrestor effectiveness of the foam material was limited partly by the fact that arrestor burning can occur under such partially packed conditions, since the foam material is combustible.

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INTRODUCTION

The present annual report summarizes the work performed on a classified portion of an Air Force-sponsored program, "Fire and Explosion Hazard Assessment and Prevention Techniques for Aircraft", DO 33(615)-66-5005. In this part of the program, the Bureau of Mines is investigating the effectiveness of cellular foam materials as possible flame arrestors for use in aircraft fuel systems using hydrocarbon-type fuels. Of particular interest here are certain reticulated polyurethane foams whose use would not result in prohibitive weight and fuel load penalties. The current work effort has been focused largely on the application of such materials to fire and explosion protection for our military aircraft, particularly for those in hostile combat environments. For those materials which prove to be effective, the ultimate objective of this work will be to determine optimum design configurations for various aircraft fire protection applications.

Generally, flame arrestor devices are designed to contain a number of small apertures or passages which provide sufficient surface to cool and extinguish a propagating flame. The effectiveness of a flame arrestor depends upon a number of factors including the diameter of the aperture, the length of the arrestor, and the velocity of the propagating flame.[1,2] Flame velocity (flame speed) is a function of the combustible gas composition and the container or tube dimensions and increases with an increase in the tube diameter and the flame run-up distance. In the present work, the effects of such variables were determined in flame arrestor experiments with n-butane or n-pentane-air mixtures and a reticulated polyurethane foam having a pore diameter of approximately 0.1 inch (material A - 10 pores/inch).

According to data in the literature,[3,4] tube diameters of about 0.1 inch would be expected to quench the flames of many hydrocarbon fuel-air mixtures at one atmosphere pressure. However, such quenching diameters are applicable primarily to flames traveling at their standard burning velocity, that is, 1 to 2 ft/sec for the paraffin hydrocarbons.[5] Smaller diameters than 0.1 inch are required where the flame travel is significantly greater than the standard burning velocity. The results found in the present work with the foam material at large flame run-up distances (ignition void lengths) or at elevated mixture pressures were consistent in this respect. The effectiveness of the foam material to prevent flame propagation also varied with

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1/ Palmer, K. N., "The Quenching of Flame by Perforated Sheeting and Block Flame Arrestors," Symposium on Chemical Process Hazards, Inst. Chem. Engrs., 16 Belgrave Square, London SWI, p. 51.

2/ Cubbage, P. A., "Flame Traps for Use With Town Gas/Air Mixtures," The Gas Council, 1 Grosvenor Place, London, SWI, November 1959, p. 25.

3/ "Flame Arrestors and Explosion Reliefs," Ministry of Labour, Series No. 34, H. M. Stationery Office, 423 Oxford St., London WI, 1965, p. 15

4/ Lewis, B. and von Elbe, G., Combustion, Flames and Explosions of Gases, 2d edition, Academic Press, N. Y., 1961, p. 256.

5/ Ibid, pp. 381-400.

the arrestor length, vessel diameter, mixture fuel-air ratio, and the condition (wet or dry) of the foam material. Small-scale experiments and full-scale experiments in an aircraft external fuel tank (450 gals) were conducted to obtain the data summarized in this report.

PHYSICAL AND CHEMICAL PROPERTIES OF FOAM MATERIAL A

The arrestor material used in this work was a Scott[6/] industrial foam ("Z" type) which is classified as an ester-type polyurethane. This material has an open pore structure and is composed of a three-dimensional network of interconnecting strands. According to the vendor's specifications (table 1), the porosity of the present foam is given as 10 pores per lineal inch with a tolerance of plus 5 and minus 2 pores per inch; the void volume is approximately 97 percent of the total gross volume. The vendor's claims indicate that the foam is not affected chemically by oils, solvents, or greases at normal temperatures; also, aliphatic hydrocarbons produce slight swelling but aromatic hydrocarbons produce considerable swelling. In addition, it is reported that the foam melts with decomposition at temperatures above 525°F. Table 1 lists some of the physical properties of this material.

TABLE 1. - Physical Properties of Polyurethane Foam[1/] (Material A)

Porosity	- 10 pores (+5/-2) per lineal inch
Void Volume	- Approx. 97% of total volume
Specific surface area	- 145 ft^2/ft^3
Cell-side diameter	- 2000 microns (average)
Tensile strength	- 20 psi (average)
	- 12 psi (minimum)
Tear strength	- 6.0 psi (average)
	- 3.0 psi (minimum)
Elongation	- 300% (average)
(% of original length)	- 150% (minimum)
Resistance to air flow at 350 ft/min (800 SCFM)	- 0.045 inches of water - 1/2" sample thickness
	- 0.08 " " 1" " "
	- 0.16 " " 2" " "

1/ Scott Paper Company, Foam Division, Chester, Pennsylvania Product Data Form 2677 (1963), Test Report 2680 (1962).

EXPERIMENTAL APPARATUS AND PROCEDURE

The flame arrestor effectiveness of the reticulated foam material was investigated in small-scale and full-scale flame propagation experiments

6/ Reference to trade names is for information only and endorsement by the Bureau of Mines is not implied.

with gas mixtures of representative hydrocarbon fuels and air at ambient temperature (70° to 80°F) and various pressures. Near-stoichiometric mixtures of n-pentane or n-butane and air were used in most of the work. In the small-scale experiments, the effectiveness of cylindrical segments of the arrestor material to prevent propagation was examined in 2, 6 and 12-1/4-inch diameter test chambers at 0 to 20 psig initial mixture pressures. The full-scale tests with cylindrical arrestor segments were performed at 0 psig in a 450-gallon (60 ft^3) aircraft fuel tank. Other experiments were conducted in a 12 ft^3 vessel (23-1/2 inches diameter) with arrestor models having single or multiple cubic gross voids. The apparatuses and experimental procedure employed with each one are described below.

1. Small-scale Experiments With Cylindrical Arrestor Segments

Initial experiments were conducted with the foam material in a 2-inch diameter Pyrex tube, 20 or 48 inches long, mounted vertically. The experiments were designed to determine the relative importance of certain variables which may influence the effectiveness of the foam material as a flame arrestor. Two types of experiments were performed. In the first, the length of arrestor segment (ℓ_2) required to prevent flame propagation at various flame-run-up distances or ignition void lengths (ℓ_1) was determined with 2.4 percent n-pentane-air mixtures at various initial pressures; the void distance (ℓ_3) downstream of the arrestor was also varied. In the second, similar information was obtained but with the ignition or flame run-up void (ℓ_1) between arrestor segments that filled the rest of the flammability tube (see figure 1). Figure 1 shows a photograph of such an experimental arrangement in which the ignition void length was 3 inches and the length of each arrestor segment (2) was 8-1/2 inches; here, ignition of a n-pentane-air mixture by an electrical spark at 0 psig resulted in flame that propagated approximately 4-1/2 inches through the arrestor material before being quenched (figure 1). In such experiments, pressure rise measurements and visual observations were used to determine the extent of flame propagation; a strain gage-type transducer was mounted at the top end of the flammability tube for the pressure measurements which were recorded on a pen-oscillograph.

Most of the small-scale experiments were conducted in cylindrical steel vessels of 6-inch diameter (60 inches long) and 12-1/2-inch diameter (35-1/8 inches long) that were mounted in a horizontal position. A photograph of the experimental arrangement used with the 6-inch diameter vessel (tube) is shown in figure 2. In an experiment, a cylindrical segment of the foam material was fit into the tube at a selected distance from the ignition source, which was mounted at one end of the tube. Subsequently, the combustible gas mixture was introduced to the desired pressure and ignited by an electrical spark. The extent of flame propagation was determined from continuous pressure and temperature measurements that were made with a strain gage-type pressure transducer and 0.002-inch Chromel-Alumel thermocouples at various stations; their signal outputs were obtained on oscillograph recorders. Appearance of flame downstream of the arrestor was verified visually and by monitoring the light emission with a photovolt multiplier unit.

The above experiments were conducted with 2.4 percent n-pentane-air mixtures at various initial pressures and with various arrestor lengths (ℓ_2) and flame run-up distances (ℓ_1) in the ignition void. Other fuel concentrations were also used. The pressure rises which were produced at the various experimental conditions are given in the report as a function of the ℓ_2/ℓ_1 ratio.

2. Experiments in 12-Cubic Foot Cylindrical Vessel With Cubic Void Arrestor Models

The flame arrestor effectiveness of "cored" units of the cellular foam material was examined in some experiments with single and multiple cubic void arrestor models. Voids referred to here are in addition to those within the foam material itself. The experiments were performed in a 12 cubic foot cylindrical steel vessel, 23.5 inches in diameter and 48 inches long. In the experiments with single void arrestor units, the arrestor model was prepared in the form of a cube with 4, 6, 8 or 10-inch cubic gross voids; the arrestor wall thickness was 2 or 3 inches. Each arrestor model was covered with a 3-mil thick polyethylene wrapping to contain the combustible mixture (2.4 percent n-pentane-air mixture); models with tight fit and loose fit wrapping were employed. In each trial, the arrestor unit was centrally mounted in the 12-cubic foot test vessel which contained air. Ignition of the mixture in the arrestor unit was effected by means of a centrally located exploding wire ($\sim$ 3/8-inch length of 0.001-inch diameter copper wire). The extent of flame propagation was determined by pressure rise and temperature rise (0.002-inch thermocouples) measurements; visual observations were also made in the runs at pressure $\leq$ 5 psig where a Lucite plate was substituted for the steel cover plate of the test vessel. Initial pressure of the air in the 12-cubic foot vessel was the same as that of the combustible mixture in the arrestor unit.

A large-scale experiment was also conducted with an arrestor model having multiple gross voids and the overall dimensions of the 12-cubic foot cylindrical vessel. The model had 4 complete 8-inch cubic voids along the vertical axis with arrestor walls of 2-inch thickness; corresponding voids around the above 4 axial voids were incomplete 8-inch cubes whose open ends abutted against the vessel walls. Here, the combustible gas mixture was throughout the model and was ignited in the bottom axial gross void.

3. Full-Scale Experiments in a 450-Gallon Aircraft Fuel Tank

Three full-scale experiments were conducted with multiple arrestor sections of the foam material in a 450-gallon (60-cubic foot) aircraft fuel tank, F-105 external type. A photograph of the tank is shown in figure 3. The tank measured 21 feet long and had a cylindrical middle section (94.5 inches long) of 27-inch diameter and conical-shaped nose and tail sections, both 81 inches long. It was instrumented for the experiments with pressure transducers and fine Chromel-Alumel thermocouples (0.004-inch) at selected stations in the fuel tank; the outputs were fed to oscillograph recorders.

In these experiments, the tank was partially packed (tight fit) with various lengths of the arrestor material in the nose, middle and tail sections. The material was arranged to allow gross void spaces at both ends of each arrestor section. Total gross void volumes corresponding to 32.7, 38.1, and 46.5 percent of the tank volume were used. In each experiment, the tank was filled with a near-stoichiometric n-butane-air mixture and ignited at ambient pressure and temperature conditions. Ignition of the mixture was effected with a spark ignition source that was located in the void space between the arrestor sections in the nose and middle of the fuel tank. Extent of flame propagation was determined from the continuous pressure and temperature rise measurements and by examination of the arrestor sections after firing. Flame speeds were also calculated from the temperature-time records.

RESULTS AND DISCUSSION

1. Small-Scale Experiments With Cylindrical Arrestor Segments

The effectiveness of the reticulated foam material A (10 pores/inch) to prevent flame propagation depended on such factors as the arrestor length, flame run-up distance (or ignition void length), vessel diameter, and the composition and initial pressure of the combustible mixture. Figure 4 shows data obtained from experiments in a 2-inch diameter Pyrex tube with single arrestor segments (2-inch diameter) and 2.4 percent n-pentane-air mixtures. The arrestor length (ℓ_2) required to prevent flame propagation increased noticeably with increasing flame run-up distance (ℓ_1) and initial pressure. For example, at 0 psig the effective segment length increased from 1 to 8 inches as the run-up distance was varied from 5 to 20 inches; in comparison, the corresponding values at 10 psig increased from approximately 3 to 8 inches as ℓ_1 was varied from 2 to 5 inches. Here, if flame propagated completely through the given arrestor segment, a higher pressure rise was obtained than if the arrestor was effective, and the arrestor material was usually burned on the downstream end. Since in aircraft fuel tank applications, the arrestor material would generally be wetted by the liquid fuel present, a few experiments were also conducted at 5 psig with the foam material previously soaked in JP-6 jet fuel. Under such conditions, the effectiveness of the arrestor material increased slightly.

In the experiments in the 2-inch diameter Pyrex tube, the pressure rises increased as the gap between arrestor segments (the ignition void length-ℓ_1) and initial mixture pressure were increased. At 0 psig initial pressure, the pressure rise was only 1.5 psi for an arrestor gap of 1 inch and 25 psi for a gap of 10 inches; corresponding values for a 1-inch gap at 10 and 20 psig were about 25 and 40 psi, respectively. The data were plotted in figure 5 as a function of the arrestor length/ignition void length ratio (ℓ_2/ℓ_1 or ℓ_2'/ℓ_1); ℓ_2 and ℓ_2' were equal and refer to the lengths of the two arrestor segments. As noted, the pressure rises obtained at 0 psig initial

pressure increased noticeably with decreasing ℓ_2/ℓ_1 ratios below about 1.5; above 1.5 they varied only slightly and were below 10 psi. In comparison, the pressure rises at the elevated initial pressures (10 and 20 psig) were $\geq$ 25 psi for the range of ℓ_2/ℓ_1 ratios employed. In all cases, the pressure rises were much lower than would be expected without any flame arrestor; a pressure rise of 65 psi was obtained at an initial mixture pressure of 0 psig without the arrestor material.

Similar data on the effect of ℓ_2/ℓ_1 ratio were obtained in experiments performed in the 6 and 12-1/4-inch diameter cylindrical steel vessels. Figure 6 shows the variation of pressure rise with ℓ_2/ℓ_1 ratio for various n-pentane-air mixtures at 0 psig in the 6-inch diameter vessel (60 inches long). With mixtures containing $\sim$ 2.4 percent fuel, the pressure rises were less than 10 psi for ℓ_2/ℓ_1 ratios between 1.0 and 4.5; the ignition void length (ℓ_1) was generally 18 inches. At ℓ_2/ℓ_1 ratios < 1.0, the pressure rises increased greatly with decreasing arrestor length (ℓ_2). In addition, they were lower when the combustible mixture was more fuel lean (1.8 percent fuel) or more fuel rich (4.9 percent fuel) than the near-stoichiometric compositions that were used in most of this work. Here again, it is noted that the pressure rises were much lower than expected without the arrestor. With a 2.4 volume percent n-pentane-air mixture, a maximum pressure rise of 85 psi was obtained without any of the foam arrestor material in the test vessel.

The data points shown in figure 6 for 2.4 percent n-pentane-air mixtures are summarized in table 2 along with similar data obtained at elevated pressures (5, 10 and 15 psig). This table also indicates the extent of arrestor burning noted and lists the pressure rises expected if combustion had occurred only in the ignition void (ℓ_1), which was 18 inches in nearly all cases. At an initial pressure of 0 psig, burning occurred on the downstream face of the arrestor when the arrestor length/ignition void length ratio (ℓ_2/ℓ_1) was less than 0.5. Note that in such cases the experimental pressure rises were higher than the calculated values in table 1. At 5 psig or higher initial pressures, downstream arrestor burning was observed at an ℓ_2/ℓ_1 ratio of 1.67 (arrestor length = 30 inches). Figure 7 shows the 30-inch arrestor model and the extent of burning that occurred to the downstream ends of such an arrestor after ignitions at 0, 5, 10 and 15 psig; ℓ_2/ℓ_1 was equal to 1.67. Where downstream arrestor burning did occur, the gas temperature rises in the downstream void (ℓ_3) were of the order of 2000°F or more. According to the gas temperature rise measurements, the flame velocities at the upstream face of the arrestor were between 24 and 28 ft/sec in these experiments; they were less than these values in the downstream void, depending on the arrestor length (ℓ_2) used.

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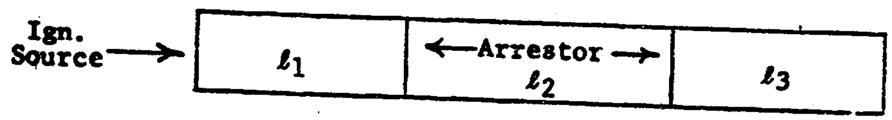
TABLE 2. - Results of Flame Arrestor Experiments in 1 ft^3 Cylindrical Steel Vessel (6-inch Diameter x 60-inch Length) With 2.4 Percent n-Pentane-Air Mixtures.



Initial Pressure psig	Arrestor Length, ℓ_2 inches	Run-Up Dist., ℓ_1 inches	ℓ_2/ℓ_1	Calc.1/ ΔP psi	Exptl. ΔP psi	Appearance2/ of flame in ℓ_3 void	Arrestor Burning
0	None	--	--	--	85.2	--	--
0	27	6	4.5	8.5	1.7	No	Upstream end - 1/8"
0	30	18	1.67	25.6	5.9	No	Upstream end - 1/2"
0	18	18	1	25.6	7.0	No	Upstream end - 3/8"
0	15	18	0.83	25.6	7.8	No	Upstream end - 1/8"
0	9	18	0.5	25.6	7.5	No	Upstream end - 3/8"
0	9	18	0.5	25.6	7.3	No	Upstream end - 1/8"
0	6	18	0.33	25.6	42.8	Yes	Downstream end - 2-1/2"
0	4.5	18	0.25	25.6	46.6	Yes	Downstream end - 2-1/2"
0	4	18	0.22	25.6	48	Yes	Downstream end - 2-1/2"
0	3	18	0.17	25.6	59	Yes	Downstream end - 2"
5	30	18	1.67	34.3	16	Yes	Downstream end - 1"
10	None	--	--	--	155	--	--
10	30	18	1.67	42.9	28	Yes	Downstream end - 1-1/2"
15	30	18	1.67	51.6	58.5	Yes	Downstream end - 1-1/2"

1/ Corresponds to expected pressure rise for combustion of gas only in the run-up void length, ℓ_1.

2/ Observations made visually and by flame sensors (thermocouple or photovolt multiplier).

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The pressure rises measured in similar experiments using the 12-1/4-inch diameter steel vessel (35-1/8 inches long) tended to be higher than those found with the 6-inch diameter vessel at the same initial pressures and ℓ_2/ℓ_1 ratios. Figure 8 shows the data obtained in this larger test vessel at 0, 5, and 10 psig initial pressures. The critical ℓ_2/ℓ_1 ratio below which the pressure rises increased greatly and downstream burning occurred was 1.5 at the initial pressure of 0 psig. At higher initial pressures (5 and 10 psig), the pressure rises were significantly higher and flame propagated through the arrestor to produce noticeable burning at the upstream and downstream arrestor faces. Figure 9 shows that the pressure rises observed in the above experiments ($\ell_2/\ell_1 = 1.67$) were greater than those found using the smaller 6-inch diameter vessel, particularly at initial pressures greater than 0 psig; at 0 psig, the differences were within experimental error. In figure 9, it is also seen that wetting the foam material with kerosine improved the effectiveness of this material as a flame arrestor markedly. For example, at an initial pressure of 10 psig, the pressure rise was approximately 10 psi with the wet material as compared to almost 30 psi with the dry material (6-inch diameter vessel). Also, no arrestor burning occurred downstream with the wet material, whereas burning was noted with the dry material in the experiments at ≥ 5 psig initial pressure and at the given ℓ_2/ℓ_1 ratio (1.67).

Figure 10 compares the data obtained in the 2, 6 and 12-1/4-inch diameter vessels at an initial pressure of 0 psig. This figure shows that the diameter effect tends to be evident at ℓ_2/ℓ_1 values less than about 1.5, although all the data are not consistent. Nevertheless, the critical ℓ_2/ℓ_1 ratio appears to be equal or less than about 1.5 for vessels of such diameters. The effect of vessel diameter is further illustrated in figure 11 where interpolated pressure rise data taken from figure 10 are plotted for ℓ_2/ℓ_1 ratios of 0.5 and 1.3. A 27.5-inch diameter data point is included and is consistent with the other data shown here; the former was obtained from an experiment in the 450-gallon aircraft fuel tank which will be discussed later in the report.

According to the data obtained from the small-scale experiments, the foam material appears to be suitable as a flame arrestor for applications at 0 psig, providing the ℓ_2/ℓ_1 ratio is greater than about 1.5. In applications where the ℓ_2/ℓ_1 ratio is very large, as for the case of fully foam-packed vessel ($\ell_2/\ell_1 \longrightarrow \infty$), the present foam would be expected to be even more effective than observed here. Not only would the pressure rises tend to be smaller than those reported above, but also the possibility of any arrestor burning would be more remote.

2. Experiments in a 12-Cubic Foot Cylindrical Steel Vessel With Single and Multiple Cubic Void Arrestor Models

The arrestor configurations in this portion of the work were designed to obtain information on the effectiveness of the flame arrestor material A for possible applications with "cored" units. In the experiments conducted

in the 12 ft^3 cylindrical steel vessel (23.5 inches diameter) with single arrestor units (64 to 1000 in^3 gross voids), the initial pressure rises increased with an increase in the volume of the arrestor cubic void. Figure 12 shows a plot of the initial pressure rises vs the total combustible gas volume/vessel volume ratio for experiments conducted at 0 psig in arrestor models having 2-inch thick walls and 4, 6, 8 or 10-inch cubic gross voids; only the arrestor units contained the combustible mixture ($\sim$2.4 percent n-pentane-air mixture) and they were fitted with a tight fit or loose fit polyethylene cover. The pressure rises were small, particularly for the models with tight fit covering, and they were less than expected theoretically without any flame arrestor material; since the walls of the loose fit models had less support, they would have been expected to fail more readily than the tight fit models. These data are also plotted as a function of the arrestor wall thickness/ignition void length (cubic void size) ratio in figure 13. According to these data, the arrestor units would be expected to fail when the wall thickness/ignition void length ratio is reduced to between about 0.3 and 0.5; this ratio corresponded to a 6-inch cubic void model in these experiments.

In some of the above experiments with the 8 and 10-inch cubic void models, secondary ignitions occurred approximately 50 seconds after the main explosion event, and these resulted in burning of the arrestor material; these also gave rise to higher pressures than indicated in figures 12 and 13. Table 3 summarizes the pressure rise data in which secondary ignitions occurred with the 8-inch cubic void model at various initial pressures (0 to 10 psig). Here, it is seen that the initial pressure rises varied between 1.2 and 4.0 psi, whereas the pressure rises associated with subsequent burning varied between 10 and 64 psi.

Similar results were found using an arrestor model having multiple gross voids and with the combustible mixture throughout the model and test vessel containing it (figure 14). This model had four complete 8-inch cubic voids along its vertical axis; the corresponding voids around and adjacent to the 4 axial voids were incomplete 8-inch cubes whose ends abutted against the vessel walls. The arrestor wall thickness was 2 inches. In an experiment at 0 psig, a maximum pressure of 25 psig was observed after ignition (0.2 second), as compared to about 100 psig which would be expected theoretically; also, little arrestor burning was noted. However, in an experiment at 5 psig, noticeable burning had occurred in all of the 8-inch cubic cells along the vertical axis of the model (figure 15); reliable pressure measurements were not obtained in this run because of a defective pressure transducer. For applications at elevated pressures, it appears that such arrestor configurations must have much higher wall thickness/ignition void length ratios (>> 0.3) or smaller pore diameters (< 0.1 inch) to be effective.

TABLE 3. - Maximum Pressure Rises Developed in Flame Arrestor Experiments at Various Initial Pressures With Arrestor Model of 8-inch Cubic Gross Void.

Combustible Mixture - 2.4 volume percent n-pentane-air mixture
Arrestor Wall Thickness - 2 inches

Initial Pressure, psig	Pressure Rise: Initial Ignition ΔP_1 psi	Initial Ignition Δt_1 sec	Secondary Ignition and Burning ΔP_2 psi	Secondary Ignition and Burning Δt_2 sec
0	1.2	0.5	10	50
2	1.3	0.5	19	8.5
5	3.5	1.5	30	9
8	4.0	1	54	8.5
10	4.0	1	64	6.5

3. Experiments in the 450-Gallon Aircraft Fuel Tank

Generally, the data obtained in the three full-scale experiments in the 450-gallon (60 ft^3) aircraft fuel tank were consistent with those found in the small-scale experiments with cylindrical arrestor units. Here, near stoichiometric mixtures of n-butane (2.9 and 3.0 volume percent) and air were used, instead of n-pentane and air, at ambient temperature (70° to 80°F) and pressure (0 psig). The difference in fuel composition is not serious since the burning velocities, quenching distances, and other pertinent combustion properties of these hydrocarbons do not vary greatly at a given pressure and fuel-air ratio.

The experimental arrangements used in the first experiment (46.5 percent gross void, $\ell_4/\ell_3 = 1.29$) and second experiment (38.1 percent gross void, $\ell_4/\ell_3 = 1.94$) are shown in figure 16; ℓ_4 represents the length of the middle arrestor section and ℓ_3 the length of the ignition void between the nose and middle arrestor sections. The arrangement for the third experiment (32.7 percent gross void, $\ell_4/\ell_3 = 1.94$) is shown in figure 17. These figures also indicate the extent of burning that resulted to the three arrestor sections located in the nose (ℓ_2), middle (ℓ_4), and tail (ℓ_6) of the tank. The data obtained from gas temperature rise and pressure rise measurements are summarized in tables 4 and 5.

TABLE 4. - Gas Temperature, Pressure, and Flame Speed Data From Flame Arrestor Experiments in a 450-Gallon Aircraft Fuel Tank With 2.9 Percent n-Butane-Air Mixtures at 0 psig. (Arrestor material A - 10 pores/inch)

	Test No. 1 (46.5% Gross Void)				Test No. 2 (38.1% Gross Void)					
Thermocouple station1/	T_2	$T_3$2/	T_5	T_7	T_2	$T_3$2/	T_3	T_4	T_5	T_7
Distance from ign.pt.,inches	49.5	14.5	52.5	117	56.5	9	9	32	55.5	120
Peak Temp. °F	2700	1220	2280	3000	130	880	2110	170	2160	1810
Time of init.temp.rise, sec.	0.54	0.12	0.44	0.86	0.22	0.08	0.045	0.17	0.18	0.39
Flame speed, ft/sec.	7.6	10.0	10.0	13.0	25.4	9.5	16.5	15.5	23.5	25.5

Pressure transducer station	P_3	P_3	P_5
Initial peak press., psig	3.4	7.6	6.7
Time to peak press., sec.	0.25	0.20	0.22
Initial rate of press.rise, psi/sec.	23	22	29
Secondary peak press., psig	9.4	9.1	7.9
Time to peak press., sec.	0.65	0.26	0.32
Final peak press., psig	9.4	9.2	9.1
Time to peak press., sec.	0.65	0.56	0.56

1/ No. 38 B&S gage thermocouple wire (0.004" diam.).
2/ No. 28 B&S gage thermocouple wire (0.013" diam.).

TABLE 5. - Pressure and Flame Speed Data From Flame Arrestor Experiment in a 450-Gallon Aircraft Fuel Tank With 3.0 Percent n-Butane-Air Mixture at 0 psig. (Arrestor Material A - 10 pores/inch)

	Test No. 3 (32.7% Gross Void)					
Thermocouple station	T_2	T_3	T_4	T_5	T_5'	T_7
Distance from ign.pt.,inches	64	12	35.5	58.5	82.5	132.5
Time of init.temp.rise, sec.	0.54	0.09	0.42	0.54	0.70	0.87
Flame speed, ft/sec.	9.9	11.1	6.0	15.5	12.8	24.1

Pressure transducer station	P_3	P_5
Initial peak press., psig	2.1	1.4
Time, sec.	0.24	0.20
Rate of press.rise, psi/sec.	10.2	9.4
Final peak press., psig	8.3	7.7
Time, sec.	0.79	0.76

The maximum pressure rises observed in the three experiments were between 8.3 and 9.4 psi; these values compare favorably with those found in the small-scale experiments at 0 psig and equivalent arrestor length/ ignition void length ratios (see figure 10). However, arrestor burning occurred in the full-scale experiments, particularly in the nose and tail sections (figures 18, 19 and 20). According to the pressure-time records, secondary ignitions occurred in the first two experiments with 46.5 and 38.1 percent gross voids, as evidenced by secondary pressure peaks that developed (figure 21). Their initial rates of pressure rise (< 30 psi/sec) were low compared to those normally encountered in gas explosions. The rates of pressure rise in the third experiment 32.7 percent gross void) were lower and secondary pressure peaks (prior to final peak pressure) were not noticeable (figure 22).

Gas temperature rise measurements indicated that flame (or hot gases) propagated through the arrestor sections but at relatively low flame speeds, between about 5 and 25 ft/sec (tables 4 and 5). In addition, there was some evidence that flame had traveled along a narrow longitudinal channel or seam of the tank. It could not be assured that all small voids were eliminated in these tests; voids of even 0.1-0.2-inch diameter could be important in such flame propagations. Considering the above results, it appears that a more fully-packed tank or smaller pore size of foam is necessary to prevent the secondary ignitions and arrestor burning obtained here in such large size tanks.

CONCLUSIONS AND RECOMMENDATIONS

The flame arrestor effectiveness of the polyurethane foam material (10 pores/inch) decreased with an increase in the flame run-up distance (ignition void length - ℓ_1), vessel diameter, and the initial pressure of the hydrocarbon combustible mixture. For single cylindrical arrestor segments and large ignition void lengths (e.g. 18 inches), the arrestor length/ignition void length ratio (ℓ_2/ℓ_1) required to prevent pressure rises greater than 10 psi was at least 1.0 at an initial pressure of 0 psig. At lower ℓ_2/ℓ_1 ratios or at higher mixture pressures, the pressure rises tend to increase markedly and noticeable arrestor burning results.

Data from full-scale experiments at 0 psig in a 450-gallon aircraft fuel tank indicated that pressure rises are not large (< 10 psi) when the tank is packed to cover 50 volume percent with the arrestor sections (3) separated by large gross voids; however, some arrestor burning can occur. The effectiveness of the arrestor material would be expected to be greater in a fully-packed tank and the possibility of arrestor burning would be more remote. With arrestor models having 4 to 10-inch voids (i.e., relatively small ignition void lengths), the critical ℓ_2/ℓ_1 ratio appeared to be between 0.3 and 0.5 at an initial pressure of 0 psig. Wetting the arrestor material with liquid fuel can be expected to improve the flame arrestor effectiveness of the foam material greatly.

For practical applications, a flame arrestor must be designed for the environmental conditions of interest. In this respect, the present foam material appears suitable for quenching the flames of hydrocarbon fuel-air mixtures in fuel tanks fully packed with this material at one atmosphere pressure. However, it is not ideal for use at elevated pressures, or in partially-packed fuel tanks where the run-up distances are very large and the quenching diameters are less than 0.1 inch; a f[illegible]r limitation on the use of this material under these conditions is t[illegible]act that it is combustible in air. Therefore, for the latter applications, a material with a smaller pore diameter (e.g. 0.05 inch) would be preferred. Admittedly, if the foam is used in an aircraft fuel tank with liquid fuel, its flame arrestor effectiveness in the wet condition will be greater and the extent of arrestor burning will be greatly limited by the depletion of oxygen as a result of any combustion. Additional work is recommended below to obtain data that are needed for specifying optimum arrestor design configurations for various aircraft fuel tank applications.

1. Determine the effect of decreased pore size ($\sim$20 to 50 pores/inch) on the flame arrestor effectiveness of the present type of reticulated foam material at pressures to at least 20 psig.

2. Determine the effect of increased temperature ($\leq$ 200°F) on the effectiveness of the present foam material or one of smaller pore size.

3. Conduct full-scale experiments in 450-gallon fuel tank with the present type of foam material having a porosity of at least 20 pores/inch; include ignitions effected by gun-firings.

4. Obtain arrestor design data for external and internal fuel tank applications.

5. Investigate other cellular arrestor materials submitted for evaluation.

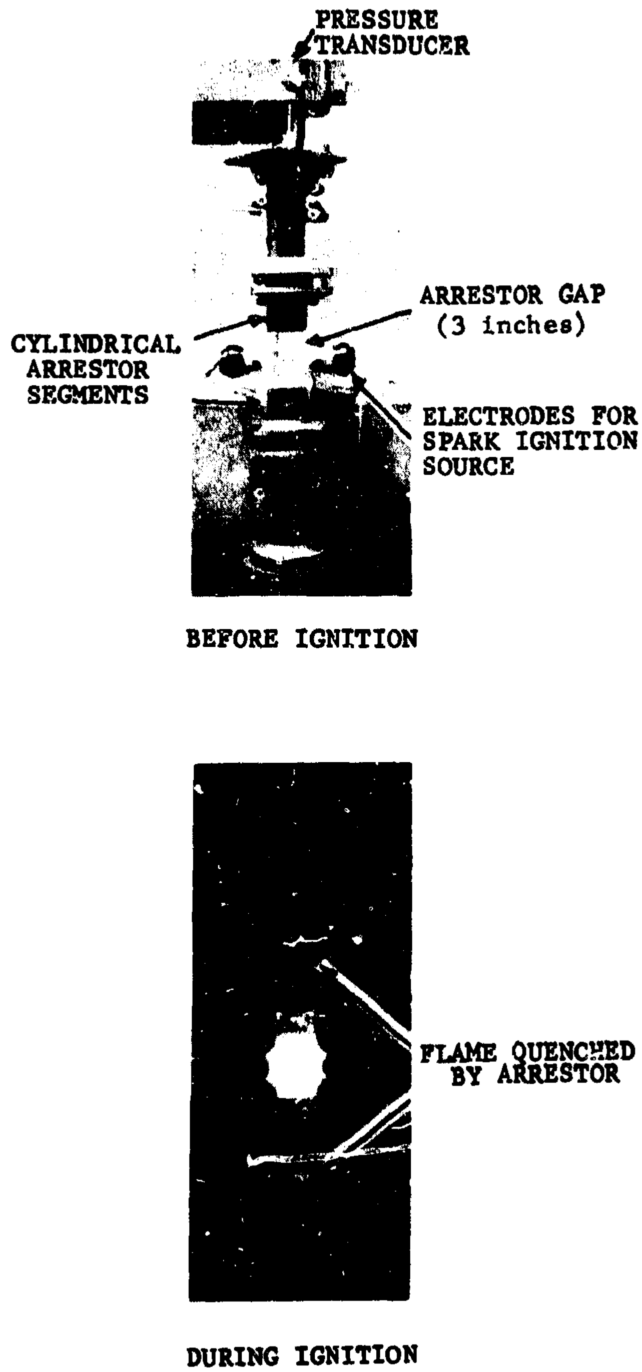


FIGURE 1. - Experimental setup for flame arrestor experiments conducted in a 2-inch ID Pyrex tube (20 inches long) with arrestor material A (10 pores/inch) and 2.4 n-pentane-air mixtures at 0 psig.

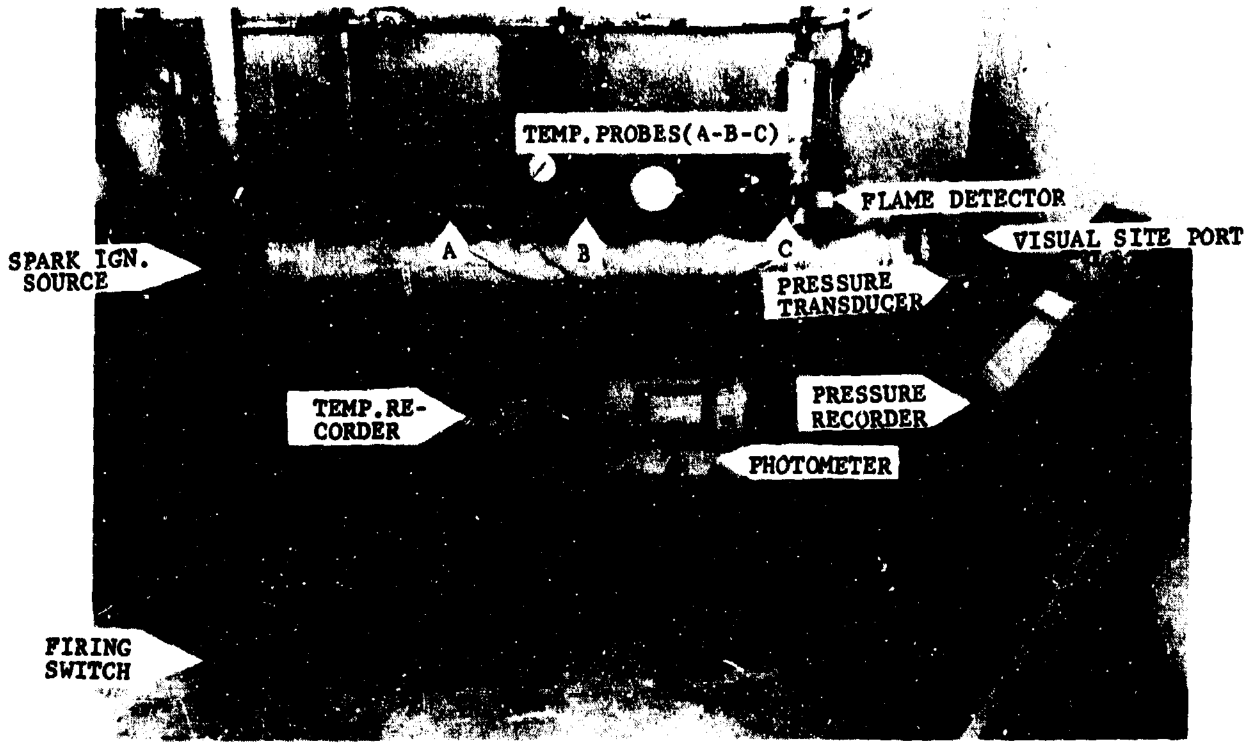


FIGURE 2. - Experimental setup for flame arrestor experiments in a 1 ft^3 cylindrical steel vessel (6" ID x 60" length).

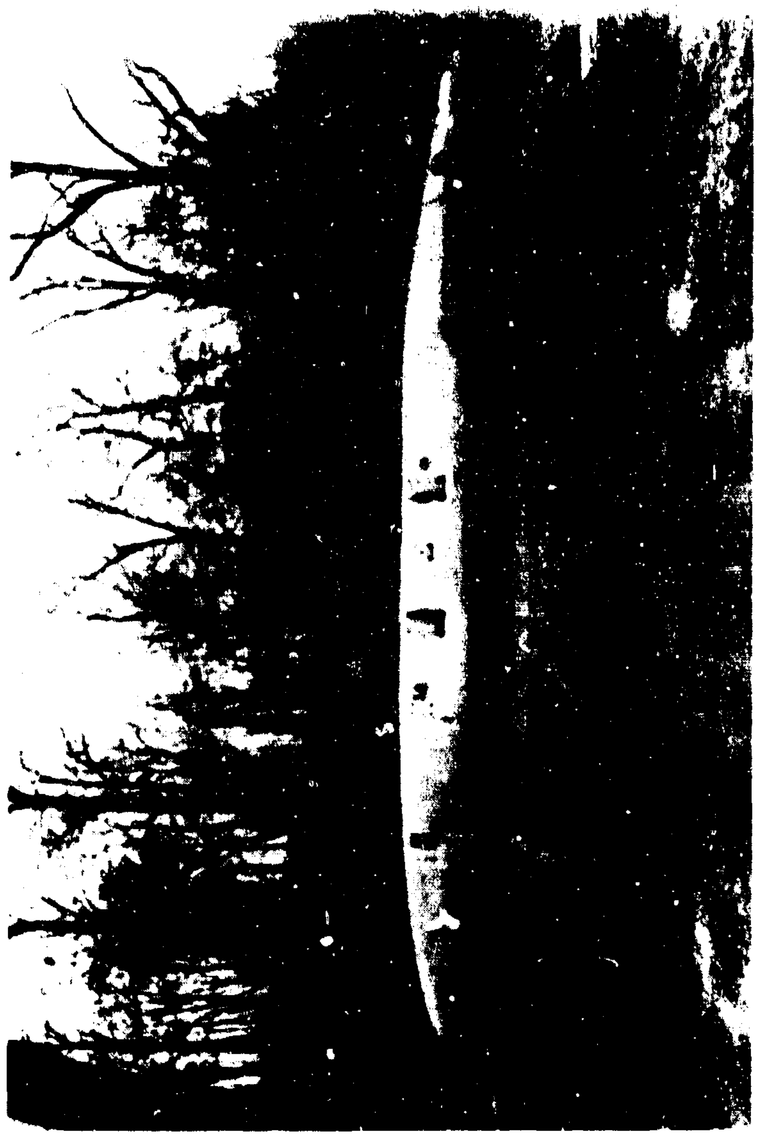


FIGURE 3. - Photograph of 450-gallon aircraft fuel tank.

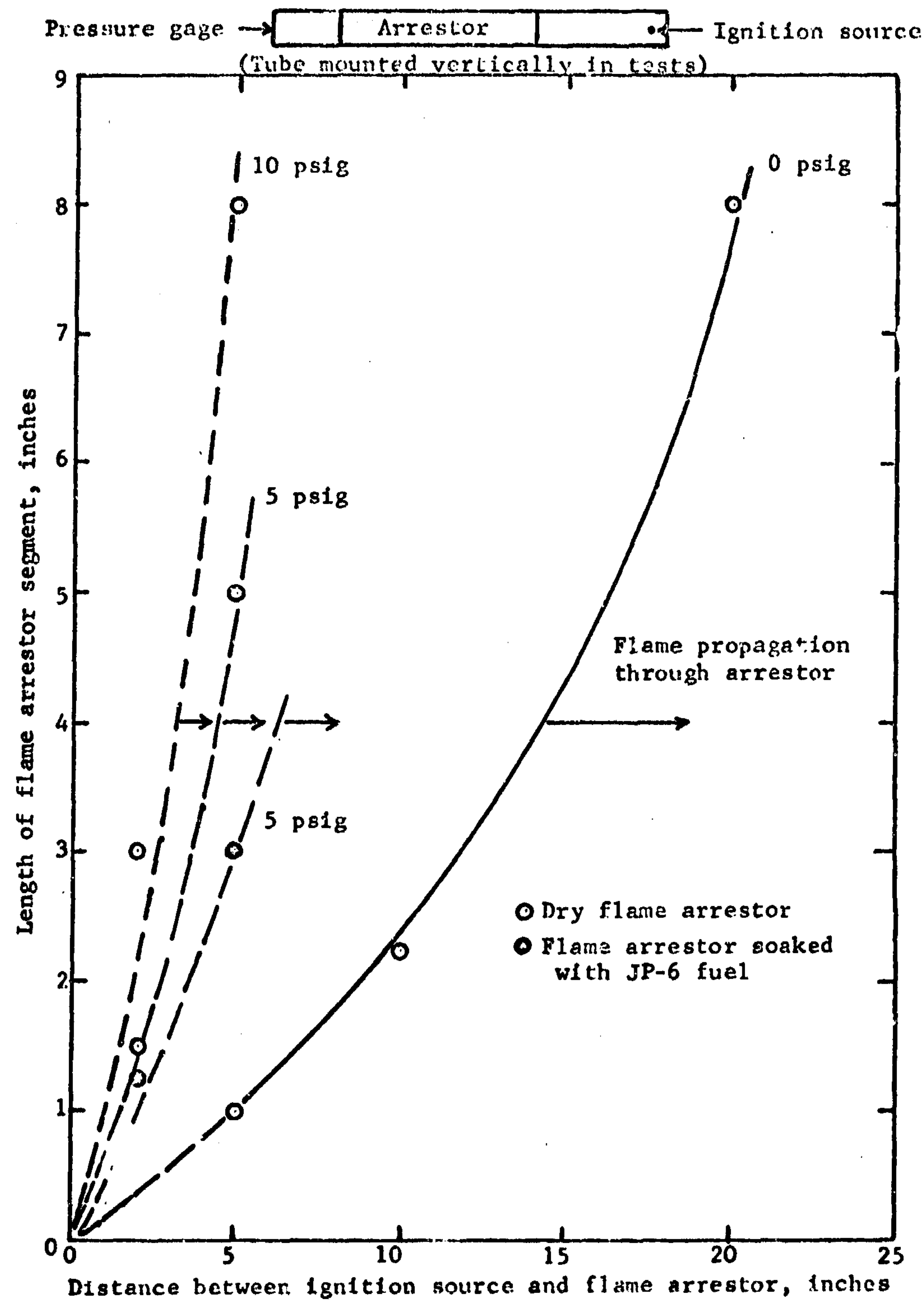


Figure 4. - Length of flame arrestor material A (10 pores/inch) to prevent flame propagation with 2.4 volume percent n-pentane-air mixtures at various initial pressures and flame run-up distances.
2-inch diameter cylindrical arrestors
2-inch diameter, 48 inches long Pyrex flammability tube

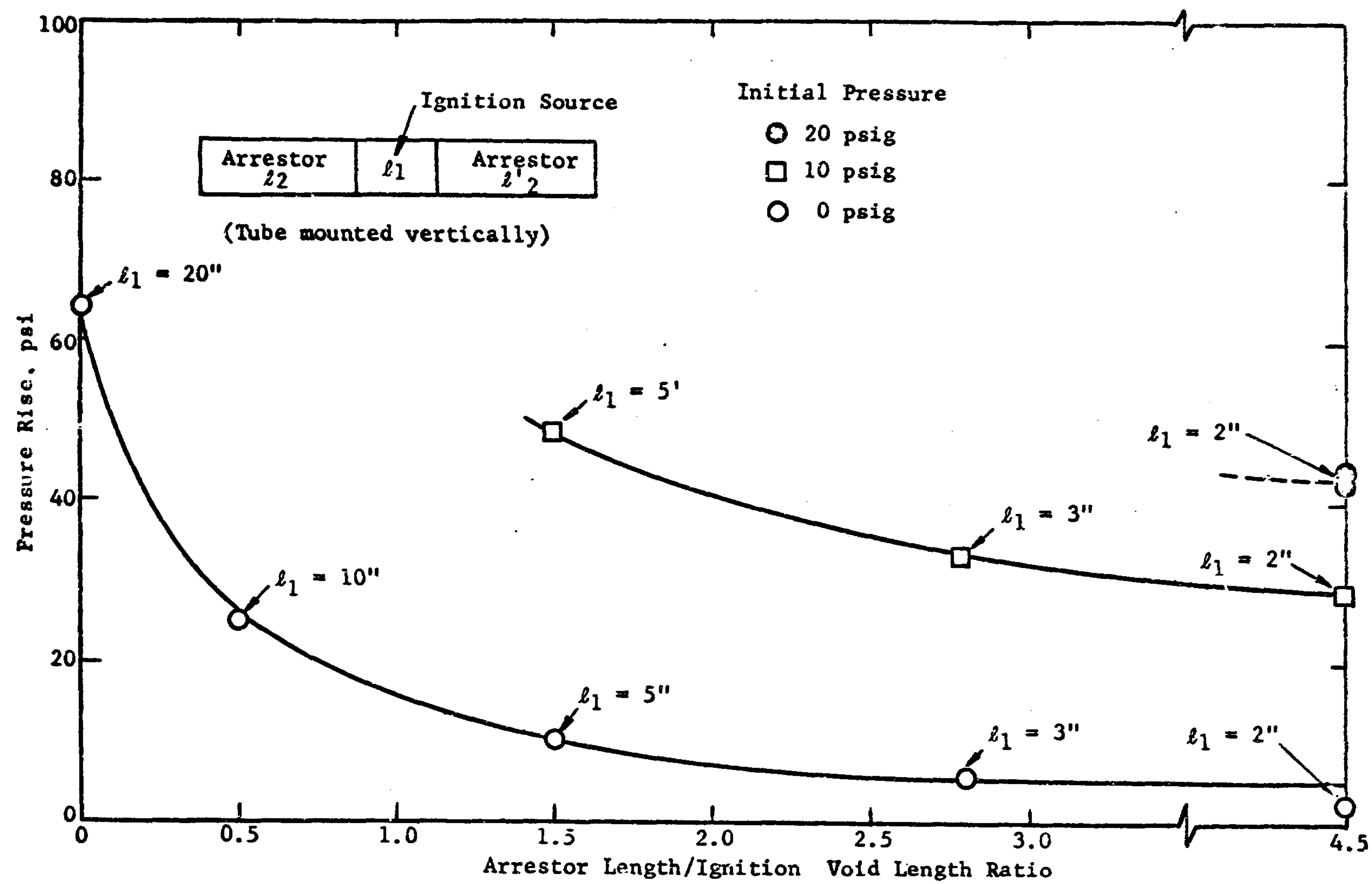


FIGURE 5. - Pressure rise vs arrestor length/ignition void length ratio (ℓ_2/ℓ_1) for experiments with arrestor material A (10 pores/inch) and 2.4 percent n-pentane-air mixtures at various initial pressures. 62.8 in^3 cylindrical Pyrex vessel - 2" ID x 20" length.

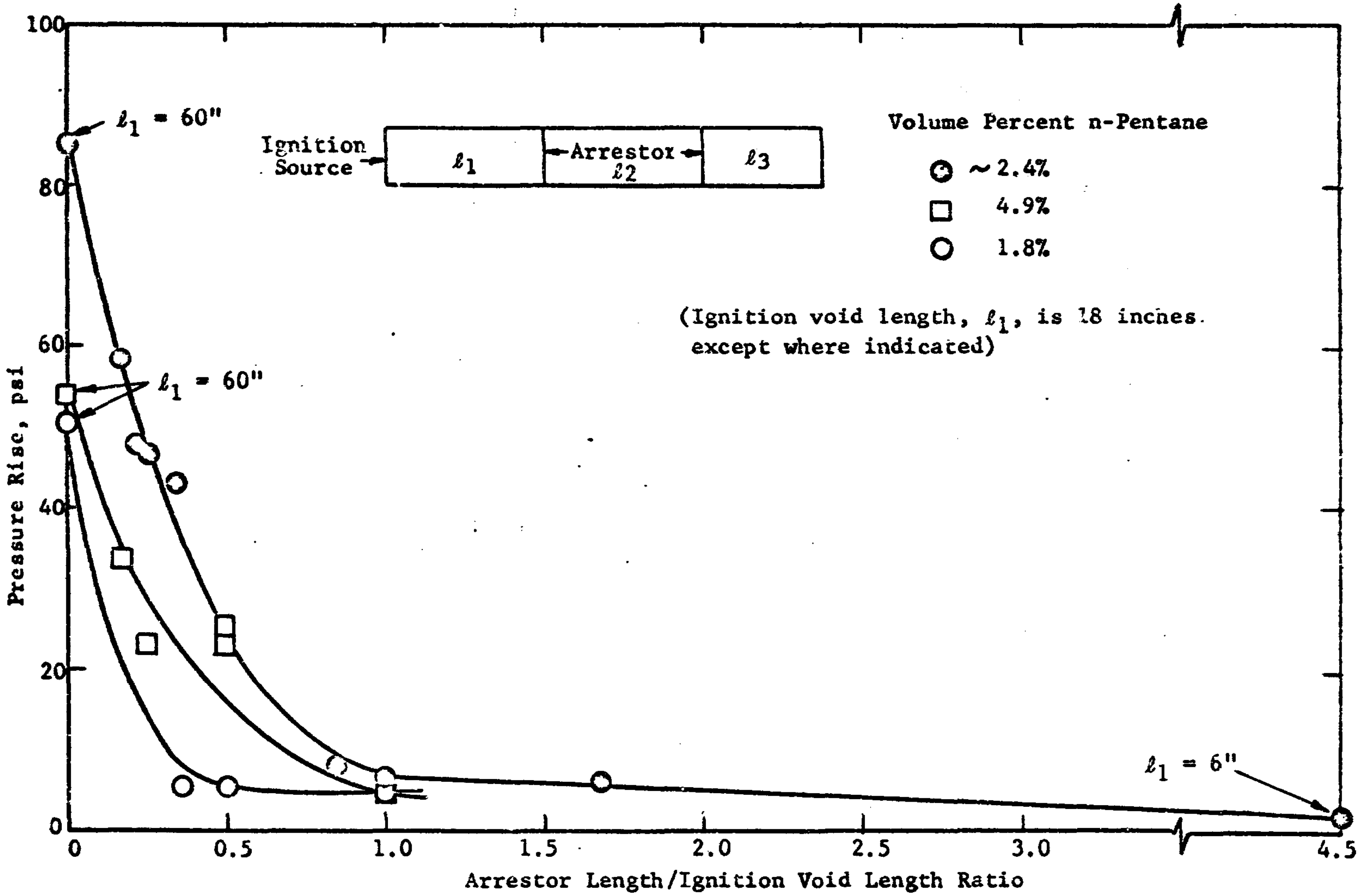


FIGURE 6. - Pressure rise vs arrestor length/ignition void length ratio (ℓ_2/ℓ_1) for experiments with arrestor material A (10 pores/inch) and various n-pentane-air mixtures at 0 psig. 1 ft^3 cylindrical steel vessel - 6" ID x 60" length.

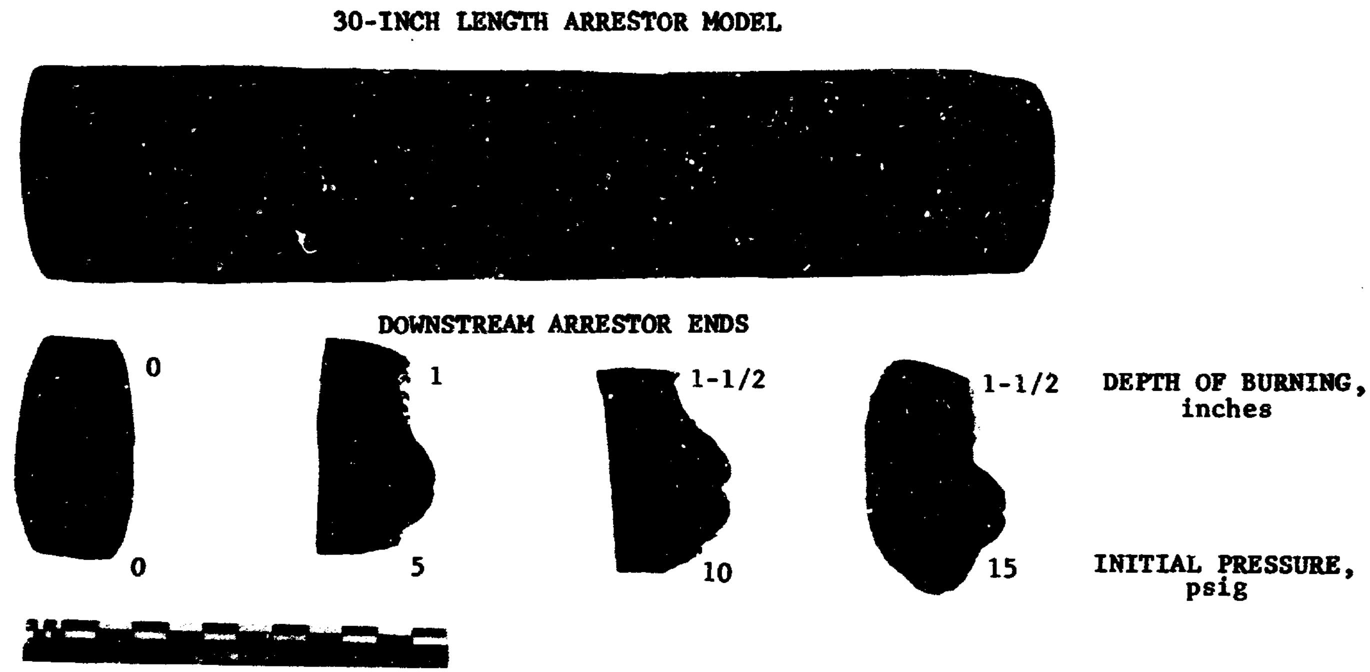


FIGURE 7. - Extent of burning at downstream end of arrestor in experiments at various initial pressures in a 6-inch diameter cylindrical steel vessel. (2.4 percent n-pentane-air).

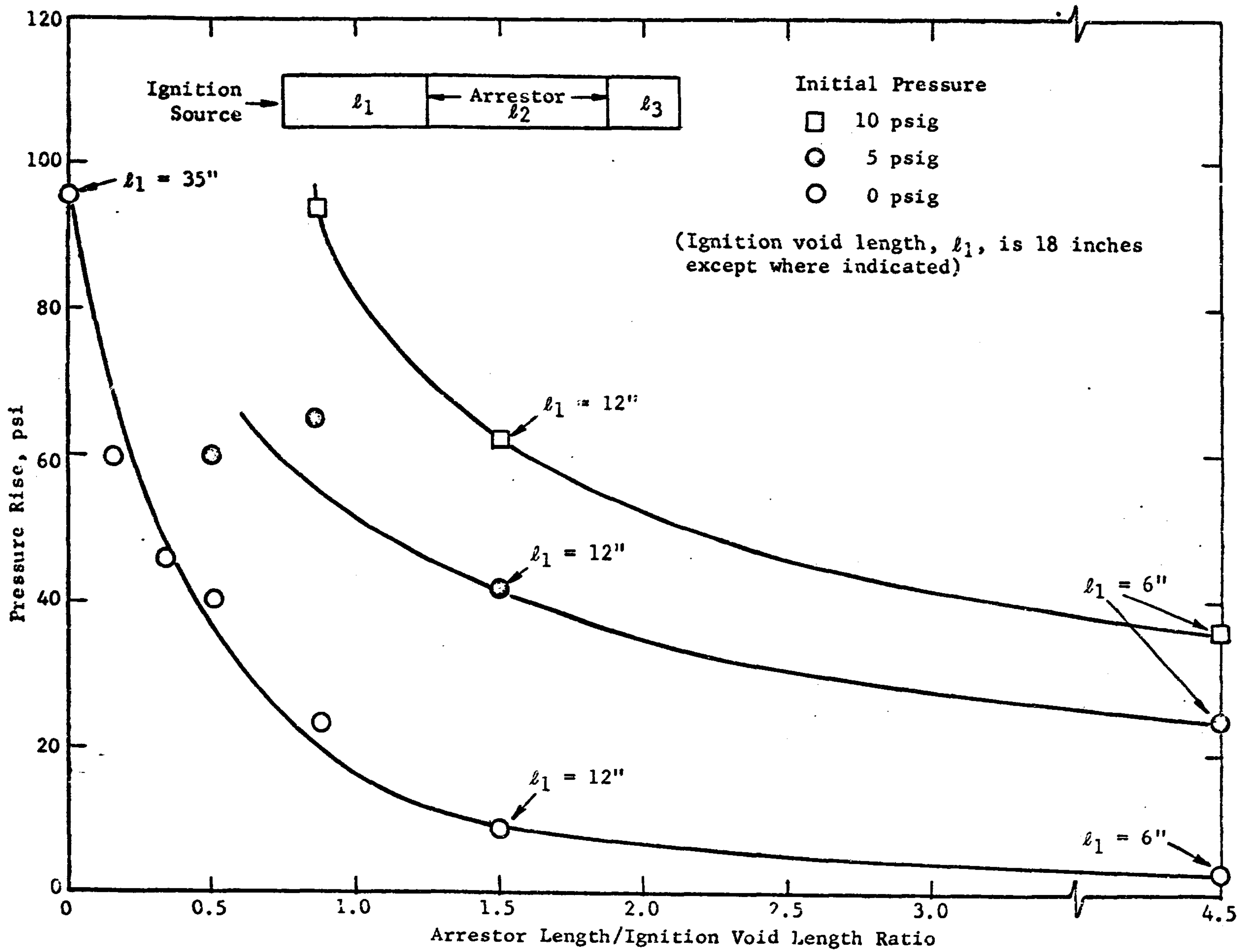


FIGURE 8. - Pressure rise vs arrestor length/ignition void length ratio (ℓ_2/ℓ_1) for experiments with arrestor material A (10 pores/inch) and 2.4 percent n-pentane-air mixtures at various initial pressures. 2.4 ft^3 cylindrical steel vessel - 12-1/4" ID x 35-1/8" length.

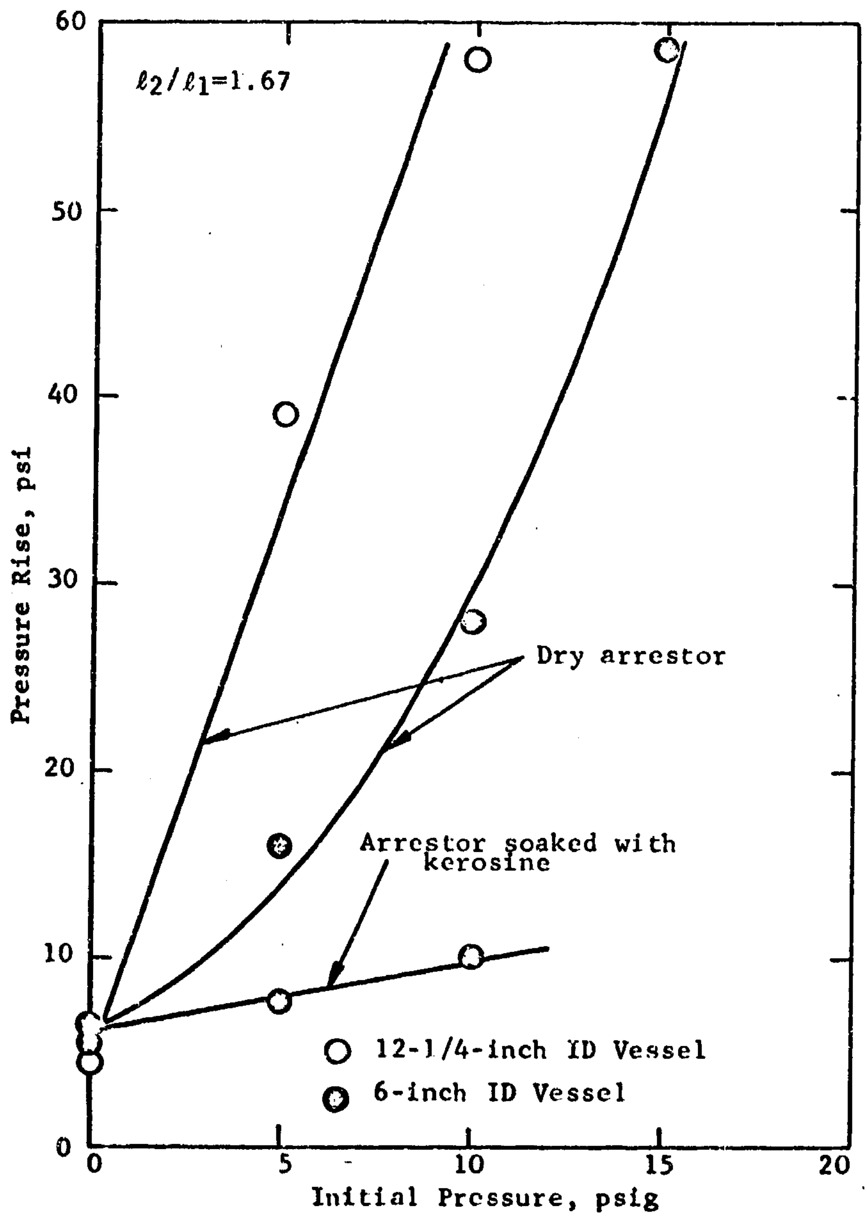


FIGURE 9. - Effect of initial pressure on pressure rise in experiments with wet and dry arrestor material A (10 pores/inch) and ~2.4 percent n-pentane-air mixtures. Arrestor length/ignition void length (ℓ_2/ℓ_1) = 1.67.

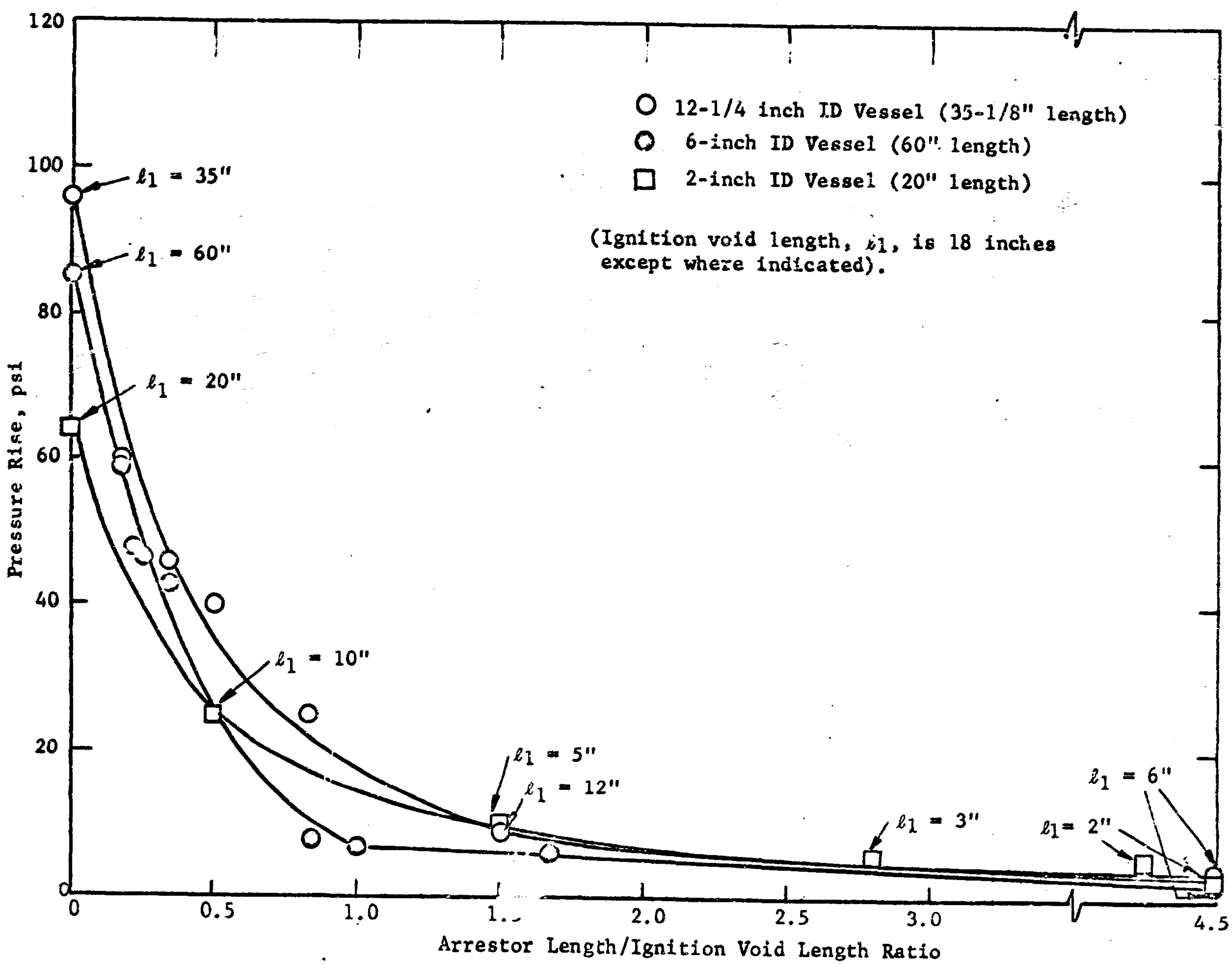


FIGURE 10. Pressure rise vs arrestor length/ignition void length ratio (ℓ_2/ℓ_1) for experiments in 2, 6, and 12-1/4-inch diameter cylindrical vessels with 2.4 percent n-pentane-air mixtures at 0 psig.

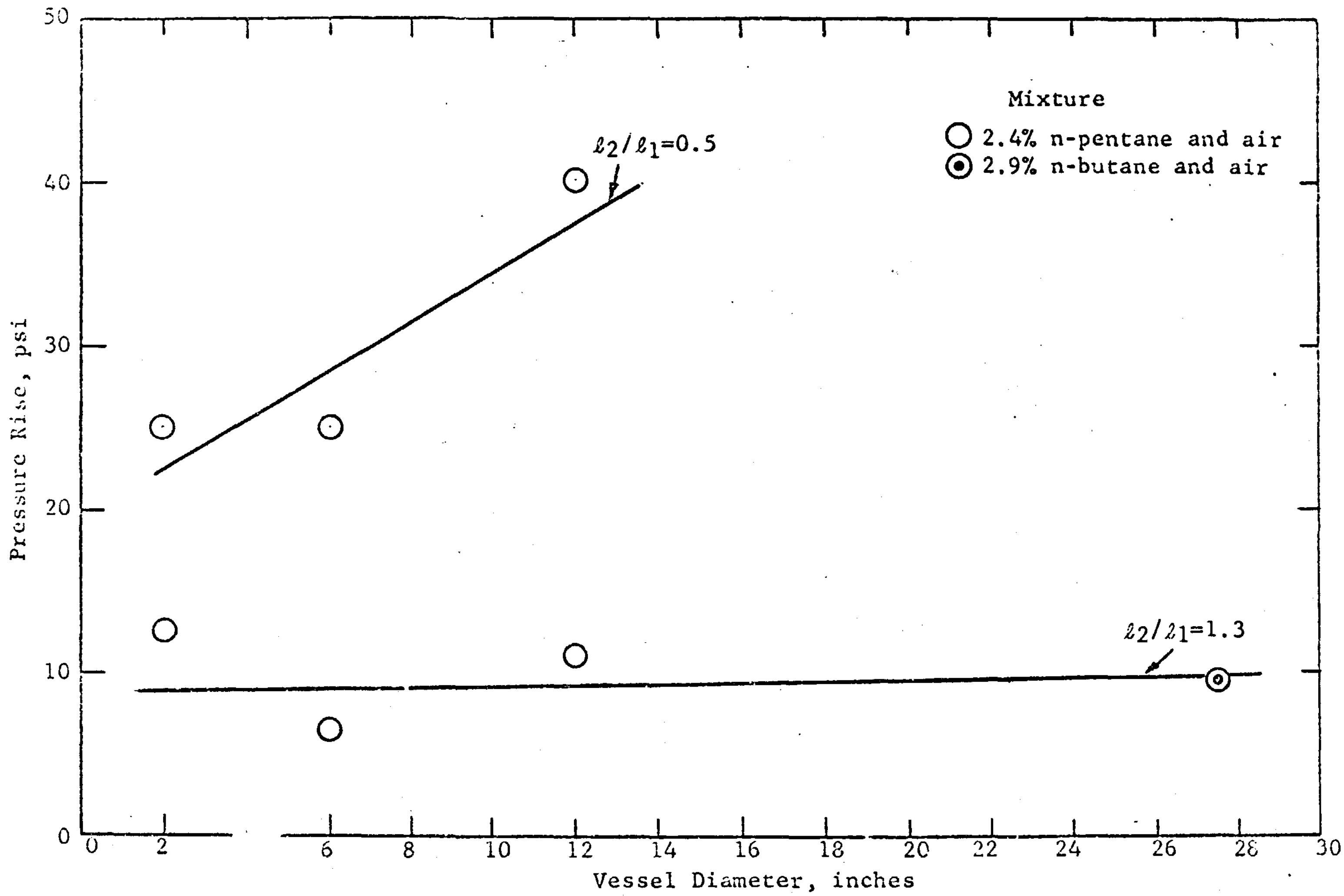


FIGURE 11. - The effect of vessel diameter on pressure rise in experiments with arrestor material A (10 pores/inch) at 0 psig and at arrestor length/ignition void length ratios of 0.5 and 1.3.

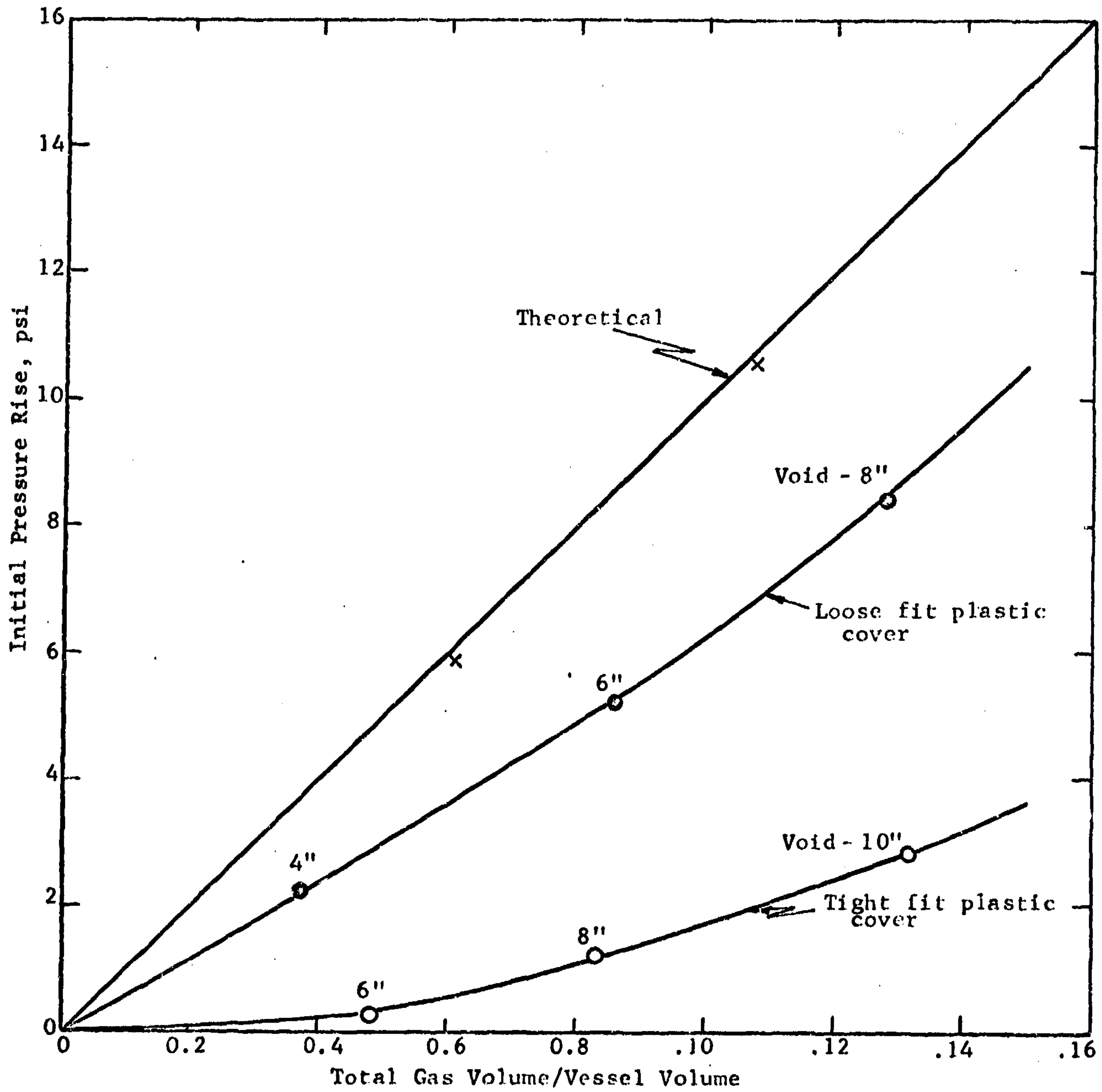


FIGURE 12. - Initial pressure rise vs total combustible gas volume/vessel volume ratio for experiments with cubic arrestor models and ~2.4 percent n-pentane-air mixtures at 0 psig.
12 ft^3 cylindrical vessel 23.5" ID x 48" length
Arrestor material A (10 pores/inch)
Arrestor wall thickness - 2 inches

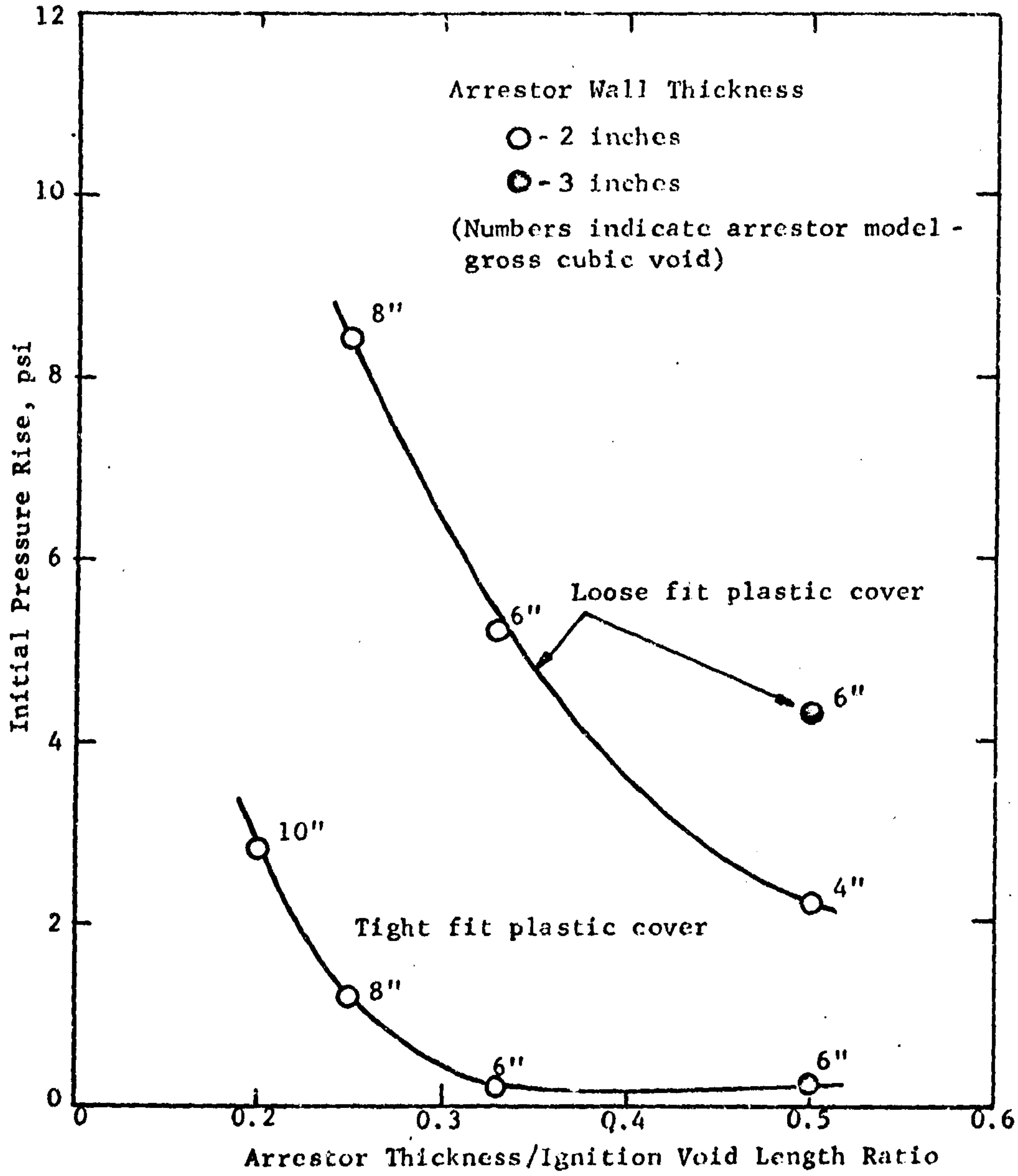


FIGURE 13. - Initial pressure rise vs arrestor wall thickness/ignition void length ratio (ℓ_2/ℓ_1) ratio for experiments with cubic arrestor models and ~2.4 percent n-pentane-air mixtures at 0 psig. 12 ft^3 cylindrical steel vessel - 23.5" ID x 48" length. Arrestor material A (10 pores/inch).

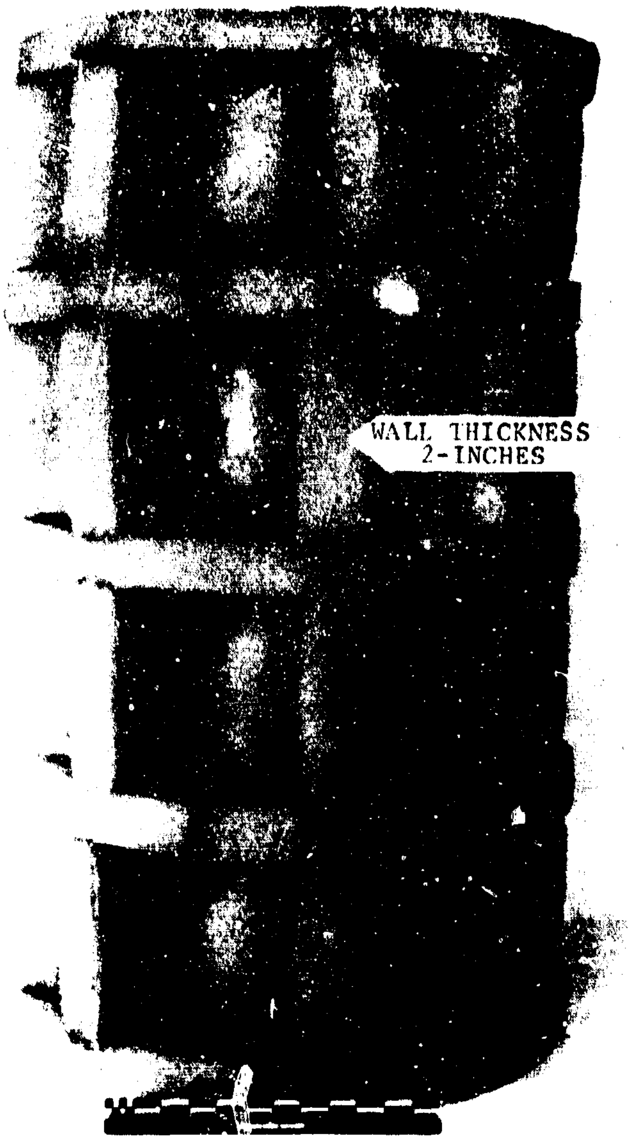


FIGURE 14. - Exterior view of arrestor model with multiple 8-inch cubic voids prior to ignition. (23-1/2" diameter x 42" length).

FIGURE 15. - Interior view of arrestor model with multiple 8-inch cubic voids after ignition of 2.4 percent n-pentane-air mixture at 5 psig. Arrestor wall thickness - 2 inches.

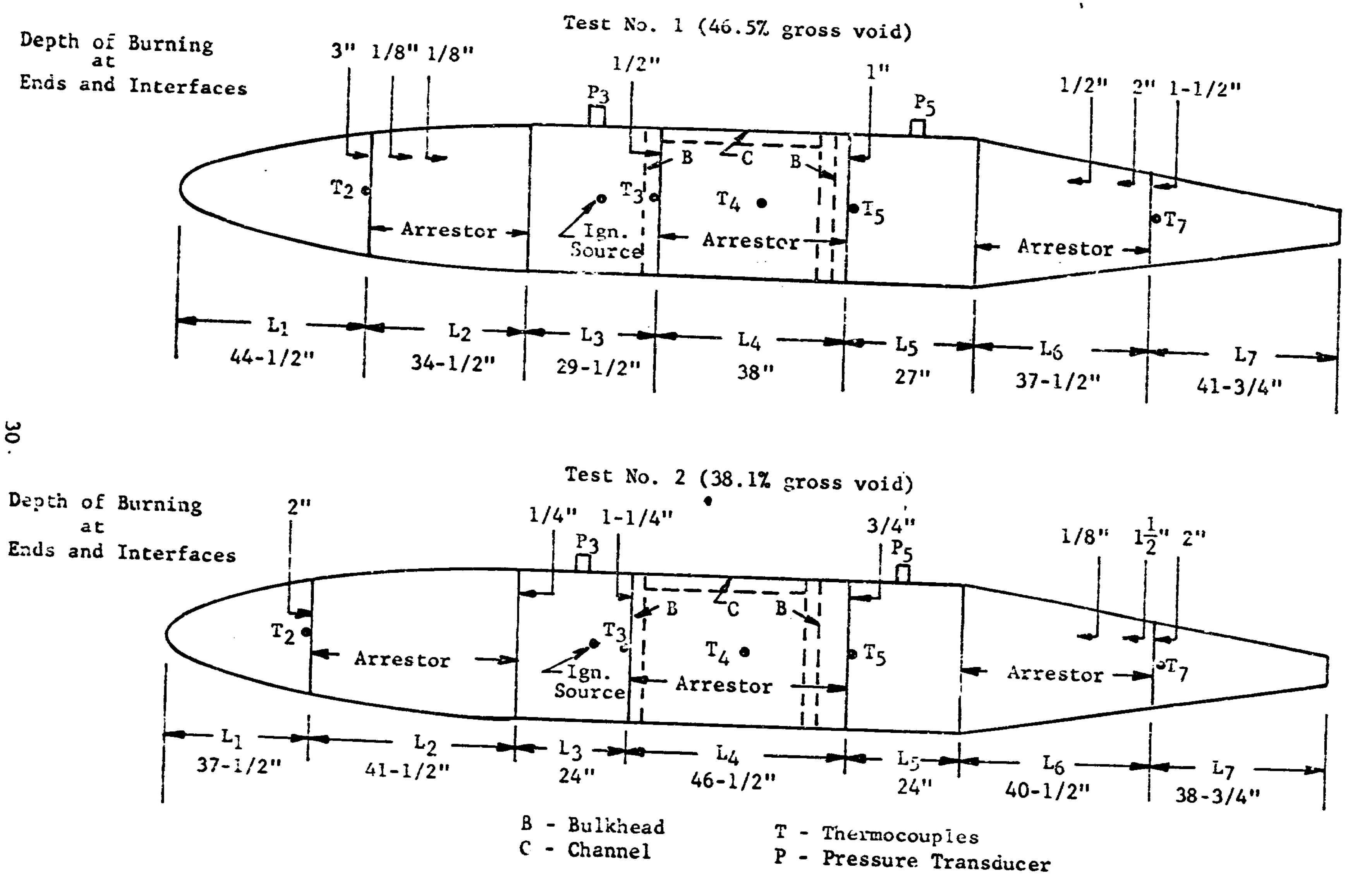


FIGURE 16. - Sketch of experimental arrangement for flame arrestor experiments in 450-gallon aircraft fuel tank (60 ft^3 volume, 27 inches maximum diameter). Extent of arrestor burning indicated for ignitions of 2.9 percent n-butane-air mixtures at 0 psig.

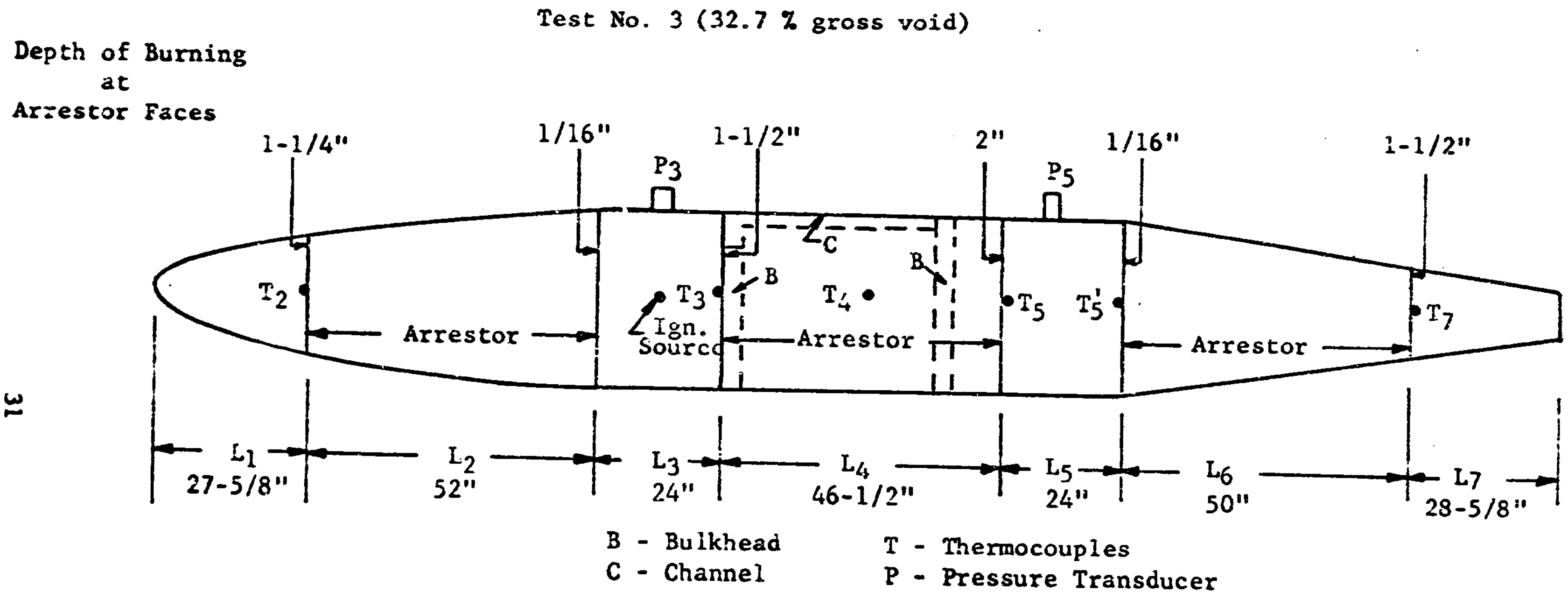
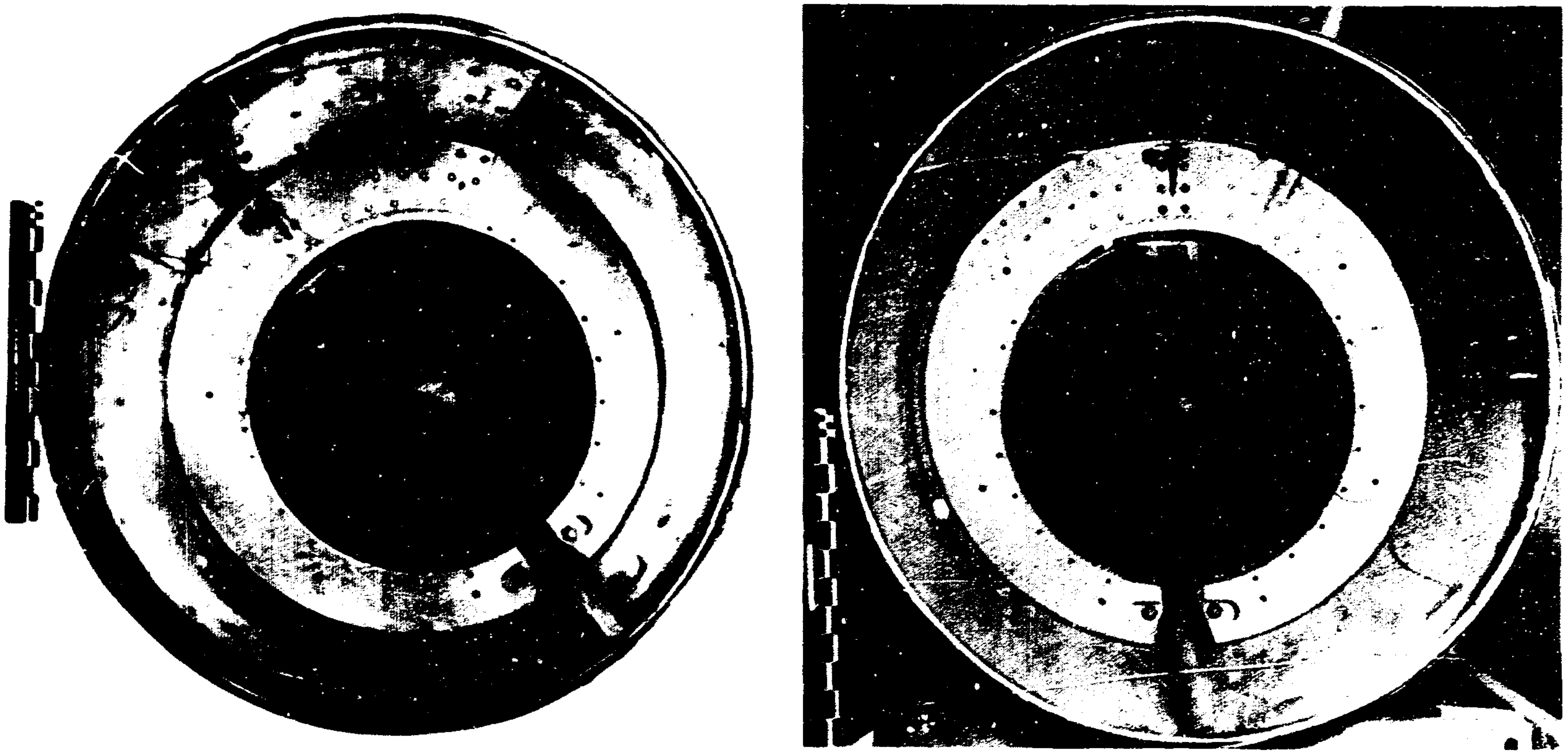
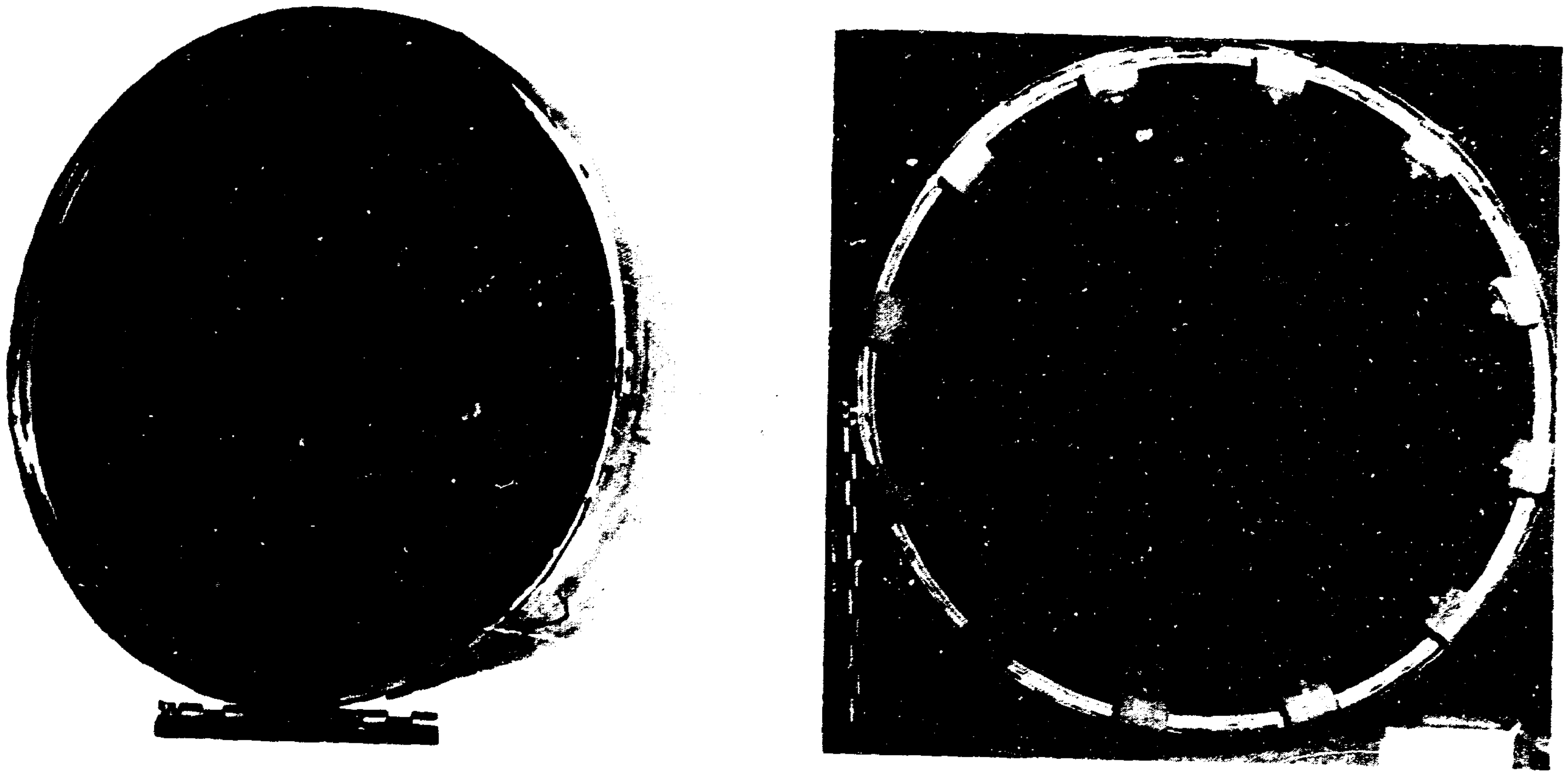


FIGURE 17. - Sketch of experimental arrangement for flame arrestor experiment in 450-gallon aircraft fuel tank (60 ft^3 volume, 27 inches maximum diameter). Extent of arrestor burning indicated for ignition of 3.0 percent n-butane-air mixture at 0 psig.



BEFORE IGNITION AFTER IGNITION

FIGURE 18. - Upstream end view of arrestor material A (1C pores/inch) in middle section (ℓ_4) of 450-gal!on aircraft fuel tank. (Test No. 1; 2.9 percent n-butane-air mixture at 0 psig).



BEFORE IGNITION

AFTER IGNITION

FIGURE 19. - Upstream end view of arrestor material A (10 pores/inch) in tail section (ℓ_6) of 450-gallon aircraft fuel tank. (Test No. 1; 2.9 n-butane-air mixture at 0 psig).

FIGURE 20. - Downstream end portion of arrestor material A (10 pores) in tail section (ℓ_6) of 450-gallon aircraft fuel tank. (Test No. 3; 3.0 percent n-butane-air mixture at 0 psig).

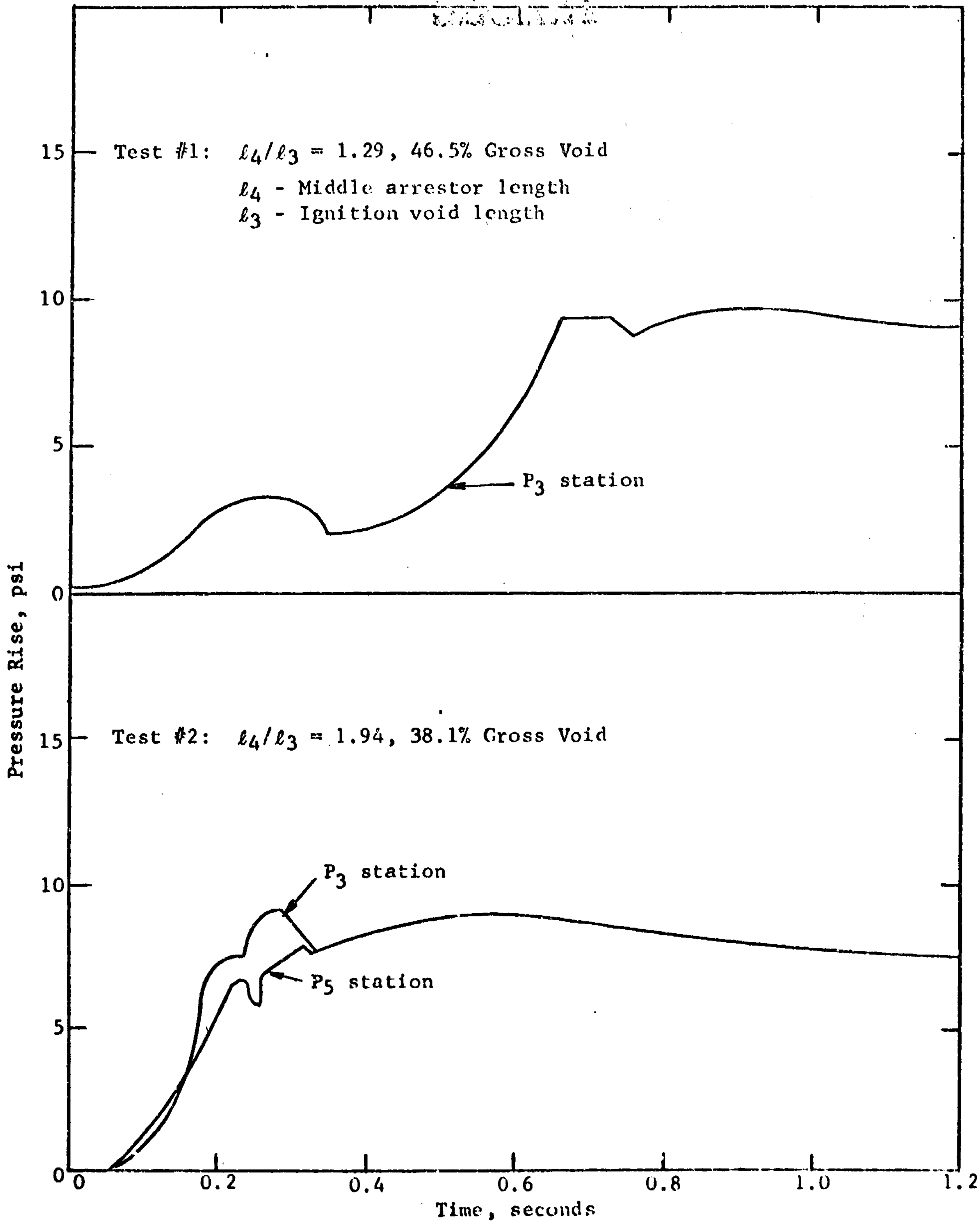


FIGURE 21. - Pressure rise vs time in experiments with arrestor material A (10 pores/inch) at 0 psig in 450-gallon aircraft fuel tank with 46.5 and 38.1 percent gross voids (free space). 2.9 volume percent n-butane-air mixture.

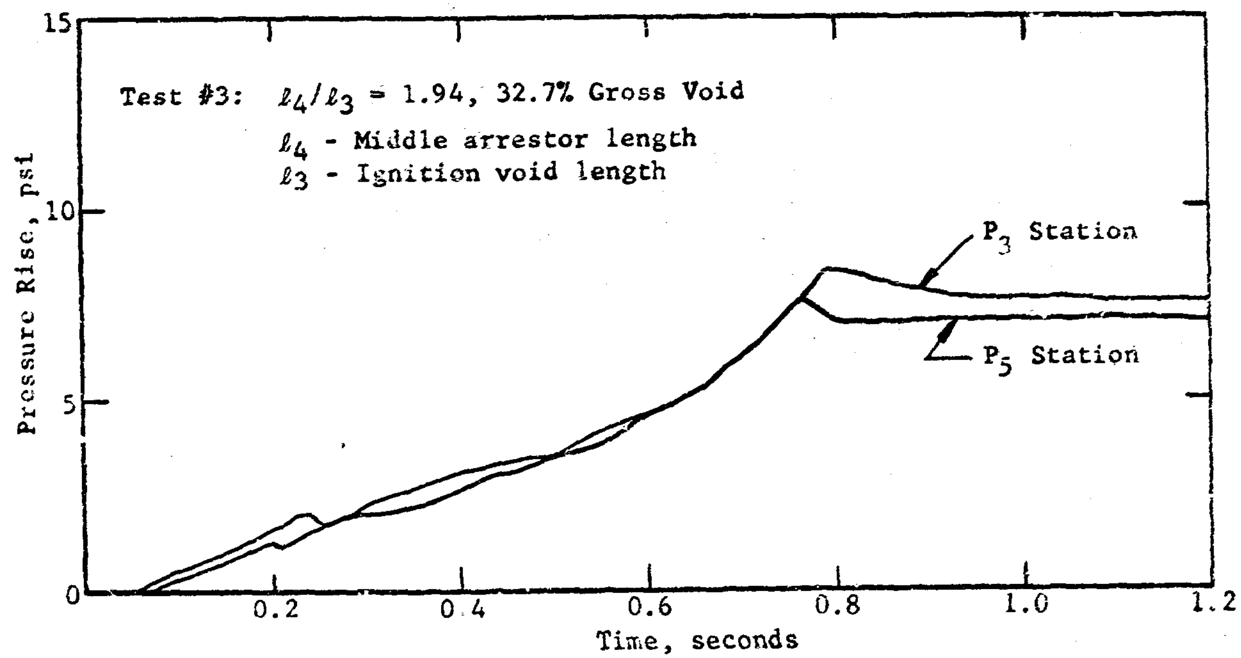


FIGURE 22. - Pressure rise vs time in experiment with arrestor material A (10 pores/inch) at 0 psig in 450-gallon aircraft fuel tank with 32.7 percent gross void (free space). 3.0 volume percent n-butane-air mixture.

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13. ABSTRACT Experimental data are presented from small-scale and full-scale experiments on the flame arrestor effectiveness of a polyurethane foam material with 10 pores/inch. Tests conducted which verified the effectiveness of the 10-pore/inch material for use in at least a fully-packed aircraft fuel tank configuration at atmospheric pressure conditions. In addition, various flame arrestor void configurations designed for external and integral fuel tank applications were examined with near-stoichiometric n-pentane or n-butane and air mixtures at various pressures (0 to 20 psig) and ambient temperature conditions. In the small-scale experiments conducted with cylindrical arrestor segments, the effectiveness of the candidate arrestor material was influenced by variations in the diameter of the test vessel, arrestor length (ℓ_2), flame run-up distance or ignition void length (ℓ_1), initial combustible mixture pressure, and fuel vapor-air ratio. Observed pressure rises at a mixture pressure of 0 psig were generally less than 10 psi at ℓ_2/ℓ_1 ratios greater than about 1.5; they increased greatly at ratios less than this value. Also, fuel-wetted arrestors were much more effective in preventing flame propagation than dry ones. Results from three full-scale experiments at 0 psig initial pressure in a 450-gallon aircraft fuel tank indicated that the pressure rises developed are relatively small (< 10 psi) when the tank is packed to about 50 volume percent or more with the dry arrestor material; the flame arrestor effectiveness of the foam material was limited partly by the fact that arrestor burning can occur under such partially packed conditions, since the foam material is combustible.

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